Aalto University
School of Chemical
Technology

School of Chemical Technology
Degree Programme of Forest Products Technology

Victoria Eklund

ALTERNATIVE APPLICATIONS AND MARKET OPPORTUNITIES FOR A NOVEL COMPOSITE MATERIAL USED IN MEDICAL APPLICATIONS

Master's thesis for the degree of Master of Science in Technology submitted for inspection, Espoo, 26th of May, 2016.

Supervisor Professor Mark Hughes

Instructor PhD Petro Lahtinen

Aalto University
School of Chemical
Technology

Aalto University, P.O. BOX 11000, 00076
AALTOwww.aalto.fi

Abstract of master's thesis

Author Victoria Eklund

Title of thesis Alternative Applications and Market Opportunities for a Novel Composite Material used in Medical Applications

Department Department of Forest Products Technology

Professorship Wood Product Technology **Code of professorship** PUU-28

Thesis supervisor Professor Mark Hughes

Thesis advisor(s) / Thesis examiner(s) PhD Petro Lahtinen

Date 26.05.2016 **Number of pages** 78+8 **Language** English

Abstract

The main goal of this thesis was to look into the material's possibilities to be used in new applications and to move into new market areas. One of the objectives was to find at least one concept, which would be worth of further development. The tensile strength, water absorption ability and behavior in vacuum moulding were tested to have references when comparing to other products. The literature review of the thesis includes information about the structural characteristics of composites and introduction of other composite materials for comparison to the material under investigation. The technical characteristics of the material are presented in this connection.

The methodology used to generate new concepts included design thinking, workshops, prototyping and screening and scoring of the concepts. Design thinking as a way of analysis gave the product development process also a social dimension, which is crucial for the further development of the product. Workshops and prototypes brought direct consumer and customer response, which was then used in the screening of the concepts. The direction of the further development was defined according to a systematic concept screening and scoring. This approach also resulted as documentation for later use.

The most important findings considering the material were the high water absorbance tendency in 70 °C and its suitability for vacuum moulding. After two iteration cycles the concept of packaging use proved to be the most potential one. The characteristics supporting the packaging use were the low working temperature of the material (~65 °C), 3D mouldability and compatibility with other materials. Limitations in production volumes and low knowledge of certain characteristics, e.g. puncture resistance and shrinkage while cooling down, are the main drawbacks for this application.

The measurements conducted in this thesis were initial, and to verify the results, the measurements should be repeated. Considering other properties, biodegradability should be taken under deeper examination. To develop the packaging concept further and to gather direct feedback from potential customers and consumers, hands-on workshops should be organized. Wider knowledge of the material properties would aid the possible new product to enter the market.

Keywords wood-plastic composite, design thinking, prototyping, biodegradable, product development

Aalto-yliopisto, PL 11000, 00076 AALTO
www.aalto.fi

Diplomityön tiivistelmä

Tekijä Victoria Eklund

Työn nimi Uudenaikaisen lääketieteellisen komposiittimateriaalin vaihtoehtoiset sovellukset ja markkinamahdollisuudet

Laitos Puunjalostustekniikan laitos

Professuuri Puutuotetekniikka **Professuurikoodi** PUU-28

Työn valvoja Professori Mark Hughes

Työn ohjaaja(t)/Työn tarkastaja(t) FT Petro Lahtinen

Päivämäärä 26.05.2016 **Sivumäärä** 78+8 **Kieli** englanti

Tiivistelmä

Tämän työn tavoitteena oli selvittää tarkastelussa olevan materiaalin mahdollisuuksia siirtyä uusiin käyttötarkoituksiin ja uusille markkinoille. Päämääränä oli löytää ainakin yksi konsepti, jota kannattaisi kehittää edelleen. Jotta vertailu muihin tuotteisiin olisi mahdollista, testattiin materiaalin vetolujuutta, veden absorptiota materialiin sekä materiaalin käytöstä alipainemuovauksessa. Tutkimuksen pohjaksi kirjallisuudesta on kerätty tietoa komposiittien rakenneominaisuuksista sekä esitelty muita puupohjaisia komposiitteja vertailun vuoksi. Materiaalin tekniset tiedot on käyty läpi tässä yhteydessä.

Uusien konseptien luomisessa käytettiin hyväksi muotoiluajattelua (design thinking), työpajoja, prototyyppien tekemistä ja konseptien karsintaa pisteyttämällä niitä. Muotoiluajattelu analyysikeinona antoi tuotekehitykselle myös sosiaalisen ulottuvuuden, mikä on tärkeää tuotteen jatkokehityksen kannalta. Työpajat ja prototyypit toivat niin ikään palautetta suoraan käyttäjiltä, mitä voitiin käyttää apuna konseptien karsinnassa. Systemaattisella konsepti-ideoiden karsimisella saatiin rajattua jatkokehityksen suuntaa ja samalla prosessista jäi dokumentaatio seuraavien projektien pohjaksi.

Keskeisimpiä tuloksia materiaalin kannalta olivat korkea veden absorbointikyky 70 °C:ssa ja sopivuus alipainemuovaukseen. Kahden karsintakierroksen jälkeen kaikkien konseptien joukosta parhaaksi osoittautui pakkauskäyttö. Pakkauskäyttöä puolsivat materiaalin matala muovauslämpötila (~65 °C), 3D-muovailtavuus sekä yhteensopivuus muiden materiaalien kanssa. Rajoittavia tekijöitä ovat tällä hetkellä tuotantomäärien rajallisuus ja liian vähäinen tieto esim. materiaalin puhkaisukestävyydestä ja kutistumisesta sen jäähtyessä.

Työn aikana tehdyt mittaukset olivat alustavia tuloksia, joiden vahvistamiseksi kokeet tulisi toistaa. Muista ominaisuuksista erityisesti biohajoavuudesta tulisi kerätä lisää tietoa. Pakkauskäyttöön liittyen suositeltavaa olisi järjestää käytännön työpajoja, joissa pystyttäisiin keräämään tietoa suoraan mahdollisilta asiakkailta ja käyttäjiltä. Laajemmat tiedot materiaalin ominaisuuksista ja vastaanotosta helpottaisivat mahdollisen uuden tuotteen pääsyä markkinoille.

Avainsanat puumuovikomposiitti, muotoiluajattelu, prototyyppi, biohajoava, tuotekehitys

ACKNOWLEDGEMENTS

"Ever tried? Ever failed? No matter. Try again. Fail again. Fail better."
–Samuel Beckett

The journey to get this work ready has not been light and straightforward, but all the more an eye opening experience. First I want to thank my supervisor and Professor Mark and instructor Petro for being patient and supporting for the whole time. I want to thank also Anssi and Karri from work, for giving me advice and knowledge regarding the material testing. Special thanks go to Professor Teppo Vienamo and all others from Aalto ARTS, who made it possible to make vacuum moulding tests. I am also grateful for the product development team at ISKU Oy for their valuable insights for the project.

The support and company of my friends has been priceless through this time. The most precious help has come from other mekanistis, who were as well writing their theses. Not to write too intensively, my Heikki has distracted me from time to time, to keep me in my right mind. I know mum has been waiting for this since the morning she saw me get my teekkarilakki (She was the only mum there at 8 o'clock on 30th of April 2010, bringing fresh doughnuts with her). My brother has been there always when needed, the best motivation penguin in the world!

It is a shame that our dad is not here anymore to see my graduation. I did it dad, wish you were here.

25th of May 2016
Cheers, Vici

TABLE OF CONTENTS

Abbreviations

CNF	Cellulose Nanofibril
FSC	Forest Stewardship Council
MDF	Medium Density Fibreboard
MUF	Melamine-Urea-Formaldehyde adhesive
NFRC	Natural Fibre Reinforced Composite
PCL	Polycaprolactone
PE	Polyethylene
PEFC	Programme for the Endorsement of Forest Certification
PET	Polyethylene terephthalate
PF	Phenol-Formaldehyde adhesive
PHA	Polyhydroxyalcanoate
PLA	Poly-lactic acid
PP	Polypropylene
PVC	Polyvinylchloride
UF	Urea-Formaldehyde adhesive
WBC	Wood-Based Composite
WPC	Wood-Plastic Composite

Terms

Anisotropy	"The quality of exhibiting properties with different values when measured along axes in different directions." (Encyclopædia Britannica Online)
Benchmarking	"The action or practice of comparing something to a benchmark; evaluation against an established standard." (Oxford English Dictionary Webpage)
Composite	"Refers to a structural material within which a fibrous material is embedded." (Encyclopædia Britannica Online)
Critical fibre length	"The minimum length of a reinforced composite fibre that will produce the maximum possible load on the fibres." (Tomsic 2000)
Proof of concept	"Evidence (usually deriving from an experiment or pilot project) demonstrating that a design concept, business idea, etc., is feasible." (Oxford English Dictionary Webpage)
T_g	Glass transition temperature i.e. the temperature, where the material transfers from a brittle to a rubbery state.
Thermoplastic	"Material that becomes soft while heating it and solid when it is cooled down. It can be repeatedly reheated and reshaped without damages." (Oxford English Dictionary Webpage)
Thermoset	"Something that cannot be melted by warming it." (Oxford English Dictionary Webpage)
Upcycling	"The operation or process of reusing waste materials to create a product of higher value or quality." (Oxford English Dictionary Webpage)

1 Introduction

1.1 Scope of the Study

This Master's Thesis was commissioned by a Finnish medical technology start-up to investigate possible novel uses for their proprietary wood composite material. Currently the wood composite is applied in manufacturing of biodegradable orthopaedic casting products with the trade name Woodcast® (Section 1.3). The thesis consists of two main phases: literature review (Chapter 2) and experimental part (Chapter 3). The results are analyzed in Chapter 4 and the final discussion is found in Chapter 5. The literature review aims to give a general overview of wood-based and other composites, to introduce Woodcast® as a material and to position Woodcast® in relation to other composite materials (Section 2.6). The experimental work (Chapter 3) is carried through with a proof of concept mentality: The material is tested for tensile strength and water absorption characteristics and compared to properties of other materials and also prototyped for vacuum moulding to see suitability for the given application.

One of the motives for new composites is the desire to develop materials to meet the unmet needs in various industries. When we already understand the observed phenomena e.g. for crack propagation, we can design materials where the dangerous stress concentrations are avoided or at least hindered (Gordon 2006). As there are probably as many characteristics as there are composites, the argument of a "better" material is rather hard to measure. Advanced composite materials bring a wide palette of new opportunities to the field of engineering, but they have their own downsides as well. The composites themselves are complex structures, which results in barriers in manufacturing and to move to larger scale production. Another major problem is the designers' lack of experience and poor knowledge of the available materials. (Sreekumar & Thomas 2008)

The balance between cost and quality is important when discussing about composites – low price is not a characteristic usually combined with new composites. This makes entering the market harder and the comparison between conventional products and composites has to be done more visibly to bring out their advantages. Another notable fact is, that often the material cost of the end product is negligible, which still promotes the use of better performing new materials.

Finding new applications for Woodcast® is a high interest for the company, as the current position in the market is relatively narrow. The multiple recoverable characteristics of the material defend the presumption for alternative uses as well. The R&D department of Onbone Oy has been working with the topic and has some suggestions already, which act as a starting point for this study. The conclusions are a combination of design, economics and material science to give a wide view of the issue from different perspectives.

The main objectives are:

- to position the material by benchmarking,
- to map new application possibilities for the material,
- to screen out one idea of the new application possibilities and
- to suggest further development model for the chosen idea.

The overall objective is to broaden the view of prospects of the material. Positioning the material in comparison to other materials, having emphasis on other composites, is of great interest. The positioning may reveal new aspects and application possibilities as well as show new market areas for the product. One of the most important goals of this study is to bring one new possible application into prototyping phase. Based on the results of the study, the feasibility of new ideas can then be analysed and taken to further development. The limiting factors concerning the commercialization are mainly related to the patent of Woodcast® (Pat. WO 2010/103186 A2). In this phase the alteration of the material itself is not of interest.

1.2 Assigning Company

Onbone Oy is a Finnish company producing Woodcast® product family. Woodcast® is used to immobilize fractures and other injuries, and at the moment it is mostly used in orthopaedic and traumatological hospital departments. The company works in a close cooperation with experts, Finnish tertiary institutions and hospitals. (Onbone Oy 2014) The product and the whole company are highly innovative-oriented and represent the forefront of development in wood-based products.

The company was founded 2008 and the first products saw the daylight 2010 in the Finnish market. In 2014 the product family consisted of 17 different products and the product was available e.g. in Finland, Sweden, Germany, Netherlands and the United Kingdom (Onbone 2014). Onbone Oy has also received the Innovation Prize of Finnish Chemical Technology (STT 2012) and a Pro Silvis –medal of the Finnish Forest Association (Suomen Metsäyhdistys ry 2012).In 2014Woodcast®competed in the New Tree Project, which aim was to find and introduce the best solutions made with wood-based materials to the public. The product won the series of Changes in Population Structure. (UusiPuu – project 2014).

1.3 The Product

Woodcast® (Figure 1) is a casting material which consists of European aspen (*Populus tremula*) wood chips and biodegradable plastic. The wood chips in the product provide a lightweight and strong reinforcement structure, which is made mouldable with the plastic matrix. (Onbone 2014) The moulding of the product is done by heating it over 62 degrees so the moulding does not require any special equipment such as water or rubber gloves. The material does not contain other constituents or toxins. (Onbone 2014)

The cast is praised for its self-adhesive character, as it attaches to other pieces of Woodcast®, cotton wool layers and other bandages, but not to the skin. Due to it high wood content it also does not feel hot either on the operating personnel or on the patient. (Lindfors & Salo 2012) The properties of the material are discussed in more detail in Section 3.1.

Figure 1 Woodcast® used in different situations. (OneMed 2014)

2 Literature Review

2.1 Overview of Composites

The definition of composite states that it is a material of two or more constituents with an identifiable interface (ASM 1987). Generally, the constituents have different chemical and/or physical properties and when combined, the characteristics of the resulting material are totally different from the original constituents (Akovali 2001). For instance, most of the materials with biological origin, such as bone or wood, are composites (Meyers et al. 2008).

Materials are mixed together to form composites not only for strength, but also for flexibility, elasticity, conductivity etc. (Gordon 2006). To give a general impression of them, the main constituents and concepts are introduced in this section. Moreover, a brief review is made on the present and the future of composite materials. The focus of this thesis remains in wood-based composites, thus they are given special attention.

There is a few ways to classify different composite types. Hollaway (1993) makes distinction between particle strengthened, discontinuous fibre reinforced, continuous fibre reinforced and laminar composites. Another approach is the classification to macro- (> 1µm) and microcomposites (< 1µm), where the division is made according to the size of the particles. If the reinforcing parts are much smaller than 25 nm, the composites are specified as nanocomposites. (Feldman 1989) In addition, composites with large usable range of deformation (i.e., based on elastomeric polymers) are called flexible composites (Lou, Chou 1992).

Features pursued by combining materials can vary largely within mechanical, physical, chemical and biological properties. Most of the composite materials are anisotropic, which means that the properties achieved may depend on the direction of measurement. This is depicted in Figure 2, which represents the different cutting directions of wood. When considering the mechanical properties, the anisotropic nature results e.g. in different tension, compression and shear bearing values. Composites consist of matrix and reinforcement, which are the main concepts dealt with them. Another noteworthy term is the interface, which describes the interaction between the matrix and the reinforcement.

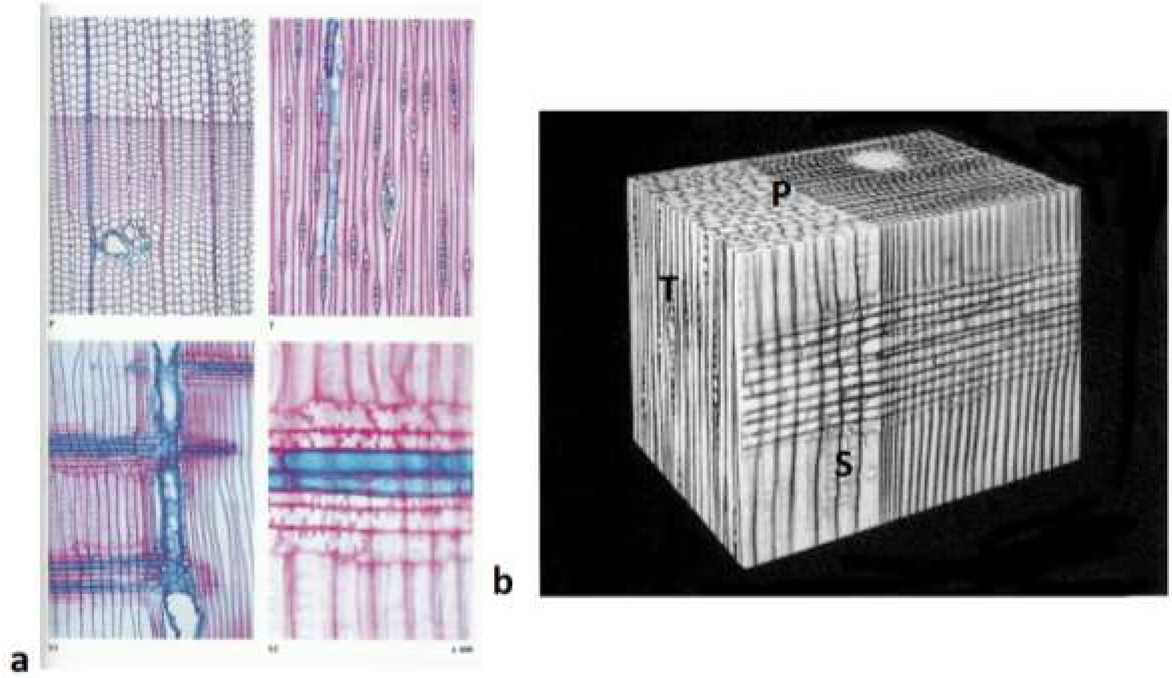


Figure 2 Example of anisotropy in natural composite materials: wood. a) Cross cut (P), tangential cut (T), and radial cut (S1 and S2) of Scots pine (*Pinus sylvestris)* (Fagerstedt et al. 2005). b) Cellular structure of wood (Dinwoodie 2000).

The reinforcement is usually fibrous, which can be in the form of particles, fibres or plates (Akovali 2001). Respectively, the composites are described as particle strengthened, discontinuous fibre reinforced or continuous fibre reinforced composites as mentioned previously. The division between these composite types depends on size, aspect ratio and volume fraction of the reinforcement. (Hollaway 1993) For example structural composites, such as sandwich panels and laminates, are considered to be a subdivision to continuous fibre reinforced composites. Further, the fibres are roughly divided to natural (fibres from animal, mineral or plant sources) and synthetic fibres. (Akovali 2001)

The main functions of the matrix are to transfer externally applied loads and to protect the reinforcement from any kind of degradation. The matrix is sometimes called binder, as it fixes the constituents together and determines the thermo-mechanical properties of the composite. It also retains the fibre orientation and spacing in specific structures. There are a great number of different matrices such as carbon, ceramic, metal, polymer and hybrid ones.

Metal and carbon matrices with good strength properties are often used in high temperature applications, where polymer matrices are unsuitable (Akovali 2001). On the other hand, polymer and hybrid matrices are used to achieve other more advanced properties: biodegradability, resilience, semi-conduction etc. Often the matrices are divided to thermoplastic (e.g., polypropylene, nylon, PVC) and thermosetting (e.g. phenol formaldehyde, vinyl ester, epoxy) materials. (Baillie 2004; Bulota 2012)

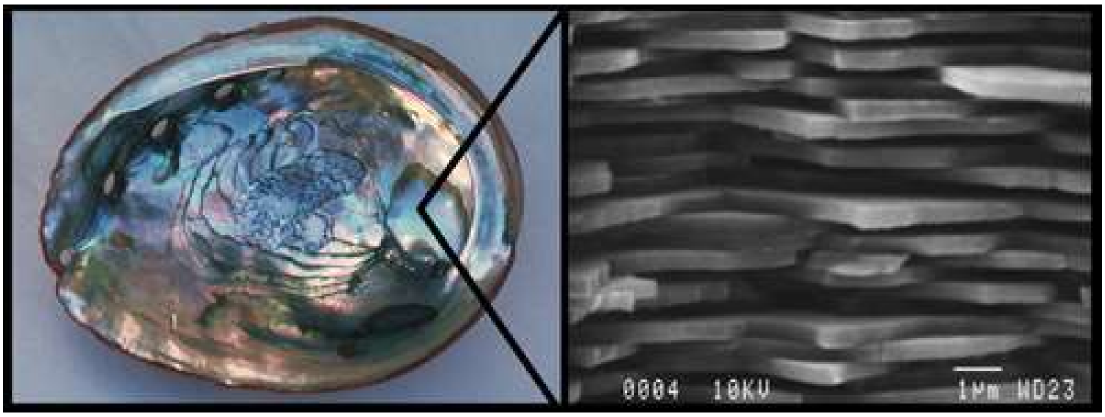


Figure 3 Abalone nacre and its microscopic structure, illustrating the composite nature of the material (Schäffer et al. 1997).

The role of the interface in a composite is to transmit loads via shear stresses; that is, to prevent crack propagation. The interface is analogous to a glue bond: if it is poor, there is no transmission of external stress and the desired properties are not achieved. But then again, if the bond is too strong, the crack propagation will not blunt in the interface. (Baillie 2004) Also the efficiency of the reinforcement is highly dependent on the particle-matrix interface (Akovali 2001). The optimization of component adhesion and interaction is hence crucial. For example in nacre (Figure 3) the weaker interfaces between hard mineral layers prevent crack propagation i.e. they are sacrificed to keep the larger structure together (Gordon 2006).

2.2 Composite Definition

There are several important characteristics to determine when dealing with composite materials such as strength, stiffness, resilience, ductility etc. Rather than aspiring just stronger and more durable materials, composites are developed to meet specified needs of certain applications. This makes the generalization of them challenging and thus this chapter gives only a superficial overview of different properties.

Stress and strain are measured to determine e.g. the modulus of elasticity also known as Young's modulus ($[E]$ = N/m²)

$$E = \frac{\sigma}{\varepsilon} \tag{1}$$

where	σ	is	stress (N/m²)
	ε	is	strain.

In particle reinforced composites ductile particles are mixed to the brittle matrix mainly to increase toughness. Vice versa, if hard and stiff particles are used in a ductile matrix, normally strength and stiffness increase. In any case the even distribution of particles is essential for effective reinforcement. (Akovali 2001)

The modulus of elasticity of unidirectional composites can be predicted with
"the rule of mixture" equations

$$E_c = (E_m V_m) + (E_p V_p) \tag{2}$$

$$(E_c')^{-1} = (E_m V_m)^{-1} + (E_p V_p)^{-1} \tag{3}$$

where	E_c	is	elastic modulus of the composite
	E_m	is	elastic modulus of the matrix
	E_p	is	elastic modulus of the particles
	V_m	is	volume fraction of the matrix
	V_p	is	volume fraction of the particles.
	E_c'	is	transverse modulus.

Equation 2 predicts the upper bound modulus, which corresponds to loading parallel to the fibres and Equation 3 predicts the lower bound modulus, which corresponds to a transverse loading. The subscripts c, m and p represent the composite, the matrix and the particles, respectively.

Other properties defined from the ratio of stress and strain are often presented as a stress-strain chart (Figure 4). Two major concepts are proportional limit, which is the point at which stress ceases to be proportional to strain (point B), and yield point of stress, which is the point where there is a transition from elastic to plastic behaviour (point C). Also resilience, the ability of a material to store elastic energy, and ductility, the amount of plastic deformation that a material can undergo before it fails, can be approximated from a stress-strain curve. It must though be taken into account that depending upon the material, there may also be delayed elastic behaviour, i.e. deformation recovers in time. (Chen & Atsuta 2008)

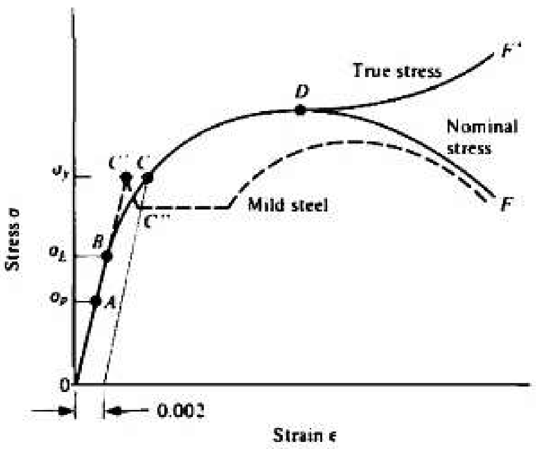


Figure 4 Stress-strain curve of mild steel, where A is the proportional limit, B is the elastic limit, C is the initial yield point, C´ is the upper yield point (under rapid loading), C´´ is the lower yield point (under constant loading, D is the maximum stress point and F is the breaking point of the material. (Chen & Atsuta 2008)

An important characteristic of a composite is the nature of its matrix. Mainly this is an issue of thermosetting and thermoplastic polymers, which both have their place in applications. Thermosets, such as epoxy, are brittle, non-rubbery and have a non-crystalline structure, and thus cannot be re-heated for reforming or recycling. Due to these features the polymers tend to degrade or burn rather than melt. (Baillie 2004)

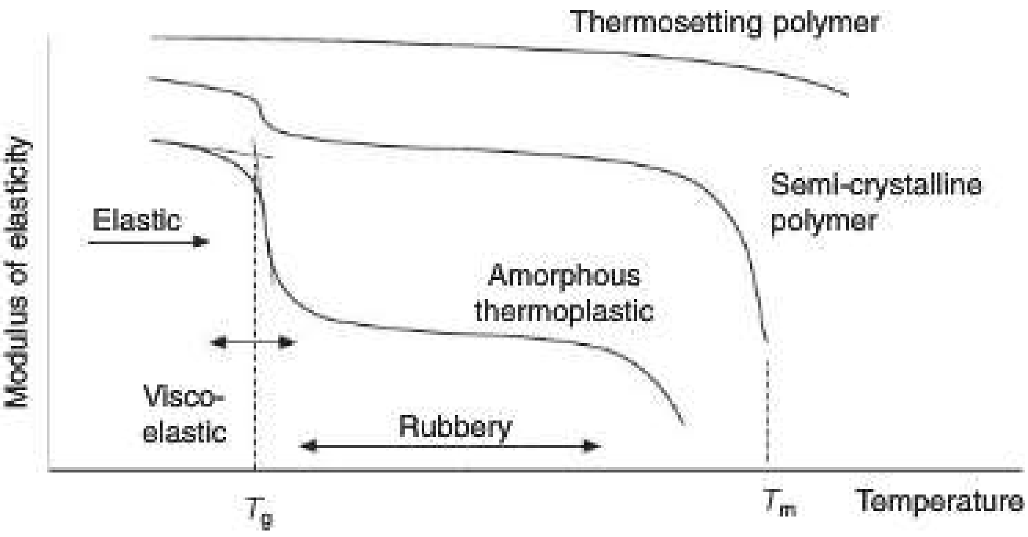


Figure 5 Young's modulus versus temperature characteristics of polymers. (T_g = glass transition temperature, T_m= melting temperature) (Baillie 2004)

Thermoplastics, such as polypropylene, have no cross-links in their structure and are generally semi-crystalline or totally crystalline. A notable property of thermoplastics is their behaviour in relation to the glass transition temperature T_g, which is depicted in Figure 5. The glass transition temperature T_g is the point, where the material moves from brittle to a rubbery state. The glass transition temperature T_g is always lower than the melting temperature T_m. These characteristics enable reforming through several cycles before degrading, but in the other hand the working temperatures are often lower than for thermosets. (Baillie 2004)

According to Akovali (2001) the reinforcement is usually 50 times stronger and 100-150 times stiffer than the matrix. Stiffness is defined as the resistance to deflection under short-term loading. When considering natural fibres their natural defects must also be taken into account, as they do not break uniformly. This links tightly to critical fibre length, which defines the maximum possible load on the fibres (Tomsic 2000).

The importance of different properties can be argued, but the toughness of the materials is often given too little attention. As J. E. Gordon (2006) notes: "The worst sin in an engineering material is not lack of strength or lack of stiffness, desirable as these properties are, but a lack of toughness, that is to say, lack of resistance to the propagation of cracks." Toughness, or work of fracture, is the resistance a material possesses to the propagation of cracks or crack-like defects that may ultimately lead to failure. (Gordon 2006)

Tough materials therefore absorb a lot of energy during the fracture process e.g. in metal the energy absorption happens through plastic deformation, where in composites several mechanisms contribute to energy absorption (Hill & Hughes 2010). Toughness is often measured as the energy required to propagate a crack through a unit thickness of material (units J/m²). Generally, there are two fracture mechanisms competing within a material: plastic flow and brittle cracking. The final fracture mechanism is determined by which of the two is weaker in the material in issue. (Gordon 2006)

To reduce the propagation of cracks, e.g. crack-blunting mechanisms are exploited. In the crack-blunting the severity of the stress concentration is reduced, as the stress is highest in the tip of the crack (Figure 6). This kind of crack-stopping is highly important in several artificial composites, such as fibre glass, but also in wood and other materials of biological origin. The difference between material cracking is depicted in Figure 7, where the progress of cracks can be easily seen. (Gordon 2006) At fibre level the hindering of crack propagation affects the strength and stiffness of the fibre and so on the same properties of the whole composite, especially resulting in fibre-matrix debonding. Additionally, fibre pull-out is reduced due to failures in the structure as the fibres rather break than are pulled out as a whole. (Hill & Hughes 2010)

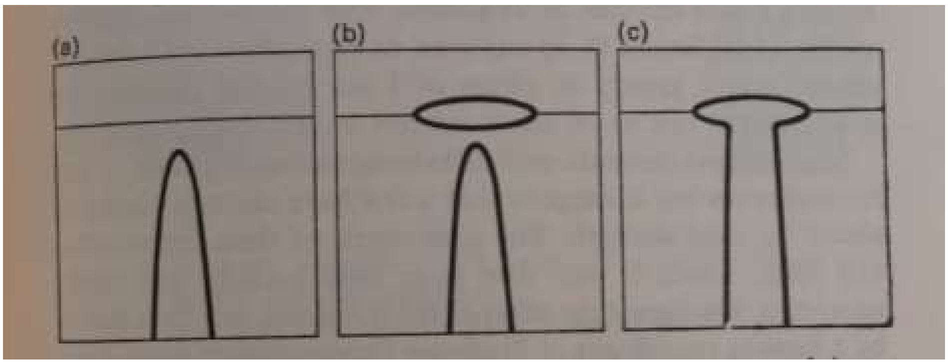


Figure 6 Crack-stopping at a weak interface. (a) Crack approaching a weak interface, (b) Interface breaking ahead of the crack, (c) T-shaped crack-stopper. (Gordon 2006)

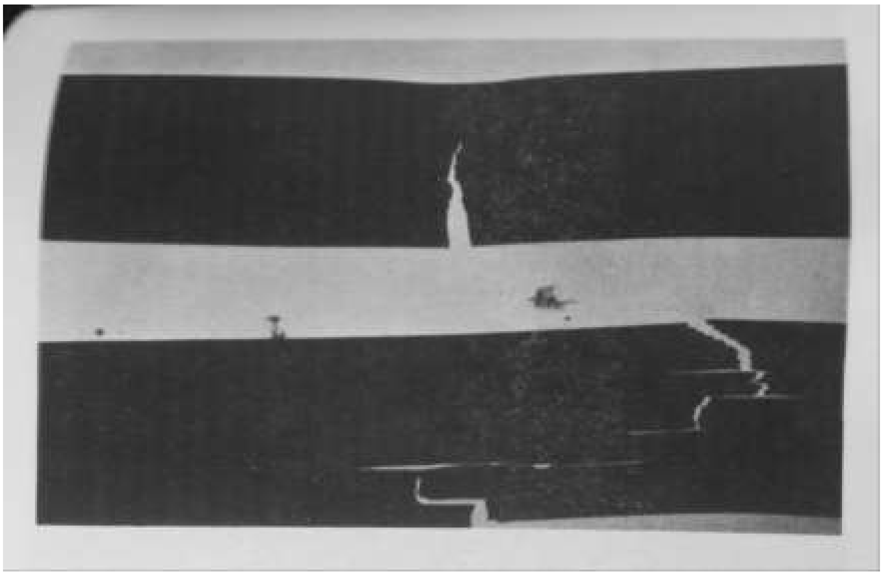


Figure 7 The upper object has no interfaces and the crack has propagated directly through the material. The lower object contains several interfaces, which has directed the cracking differently. (Gordon 2006)

Cracks or sharp changes in geometry lead to stress concentrations, which act as a mechanism to raise the local stress conditions sufficiently in order to cause failure. The effect of fibre defects on toughness and environmental stability for natural fibre reinforced composites (NFRC) is discussed in the article of Hill & Hughes (2010). They observed that e.g. in hemp fibre reinforced composite the fibre pull-out was limited and the fractures proceeded in a brittle manner.

The research shows that the fibres have compressive failures already before any mechanical processing, and the mechanical processing has severe effect on the strength of the fibre. Especially the micro-sized defects affect the toughness in a composite. Due to these reasons the NFRCs have a lack of crack-stopping features, which results in low toughness. Another notable problem with NFRCs is their moisture sorption, which results in dimensional and mechanical property changes in the composite. (Hill & Hughes 2010) The impact strength of NFRCs is also low, probably due to kink bands, which provide a crack initiation point (Eichhorn & Young 2003).

2.3 Markets and Future Trends of Biocomposites

In the 21st century the recyclability and environmental impact of all composites are more and more emphasized along with the megatrend of environmental sustainability. In the bulk market several technologies to exploit recovered fibres are under development and truly biodegradable composites are already in the market (Hill & Hughes 2010). Extending the life span of non-biodegradable composites is also a great issue. The markets are observed mainly from a European perspective.

Biocomposites, often referred to also as "eco-composites" or "green composites", are materials which are composed of constituents from renewable resources. This applies to both the matrix and the reinforcement, so that either one or both of them can be renewable. 'Fibres from renewable resources' include e.g. regenerated cellulose fibres, such as rayon or viscose, which originally come from biomass, as well as natural 'nano fibrils' of cellulose and chitin. (Baillie 2004)

Figure 8 The new central library "Käännös" in Helsinki (3D illustration). (Helsingin kaupunki 2015)

Another point of view for the future of biocomposites is the desire to develop multifunctional materials. The most usual characteristic added in comparison to conventional products is biodegradability, but also antibacteriality, life-cycle thinking, functional surfaces etc. (Ritschkoff et al., 1.12.2006). The present high-end research is heading towards applications, which are approached through synthesis of bioinspired materials and nanoscale solutions. (Meyers et al. 2008) Especially micro- and nanocellulose reinforced composites have been lately of great interest in the research field (Abdul Khalil et al. 2012; Eichhorn et al. 2010).

At the moment the bioeconomy sectors in the EU are worth over 2 billion euros and their growth is supported by different programmes. The standardization concerning biobased materials for i.e. composite use is under development and aims to unify the quality demands across Europe. (European Bioplastics e.V.P. 2013a, 2013b) The largest growing sectors for biocomposites are automotive and decking markets, where they have been utilized already for years (Taha et al. 2010). Instead of developing more powerful engines, composite materials enable weight reduction in car bodies (Gordon 2006). One interesting market area for composites to enter more strongly is the building business, which has more and more pressure to be environmentally aware.

There are several drivers for the use of biocomposites, but one of the most significant ones is the desire to reduce the amount of material going to landfill and waste disposal sites. Wood-plastic composites (WPCs) provide a way of diverting waste wood and fibres to value-added products. The story is similar for plastics, of which the majority end up in landfill. (WRAP 2015) Also the urge to develop and diversify farming practices have led to the concept of non-food crops, i.e. crops grown for the purpose of providing raw materials such as fibre and polymers for composite raw material (Réh 2013).

Figure 9 WoodCity Jätkäsaari –block in southern Helsinki (3D illustration). (SRV & Stora Enso Building and Living 2015)

In short, the goal is to make more environmentally conscious materials – sustainable composites. The main challenges that biocomposites face are cost, reliability and degree of complexities compared to other materials. On the other hand the acceptance of customers is high due to green values and the raw material availability is good compared to i.e. metals and crude oil. The image of bio-based materials and biocomposites is promoted widely in the society, which can be especially seen in large building projects. Only in Helsinki, Finland, there are three major projects utilizing wood and other bio-based materials coming: the new central library (Figure 8), WoodCity Jätkäsaari (Figure 9) and Katajanokka outdoor swimming pool (Figure 10). Although the projects are promoted as "wooden buildings", most of the materials are in fact wood-based composites.

Figure 10 "Allas" outdoorswimmingpool at Katajanokka, Helsinki (3D illustration). (Kulttuuritehdas Korjaamo 2015)

2.4 Commercially Significant Wood-Based Composites

Although wood itself is a natural composite, its characteristics are widely exploited as a reinforcement material. In wood, hemicelluloses and lignin act as the matrix as the cellulose reinforces the structure. (Hill & Hughes 2010) The wood-based composites introduced in this chapter represent so-called traditional composites, apart from the last two chapters handling nanocellulose reinforced and wood-plastic composites.

2.4.1 Plywood

The manufacturing process of plywood (Figure 11) is long, having several phases requiring time and notable amounts of energy. The large amount of steps also makes the manufacturing vulnerable for disturbances and faults, which easily affect the product quality. Also the quality of veneers varies greatly and the flaws are hard to trace in the beginning of the process, which results in significant amount of by-products to be used e.g. for energy production. There are slight differences in the manufacturing process depending on the wood species and the end use of the product. The main products in Finland are spruce and birch plywood.(Koponen 2002)

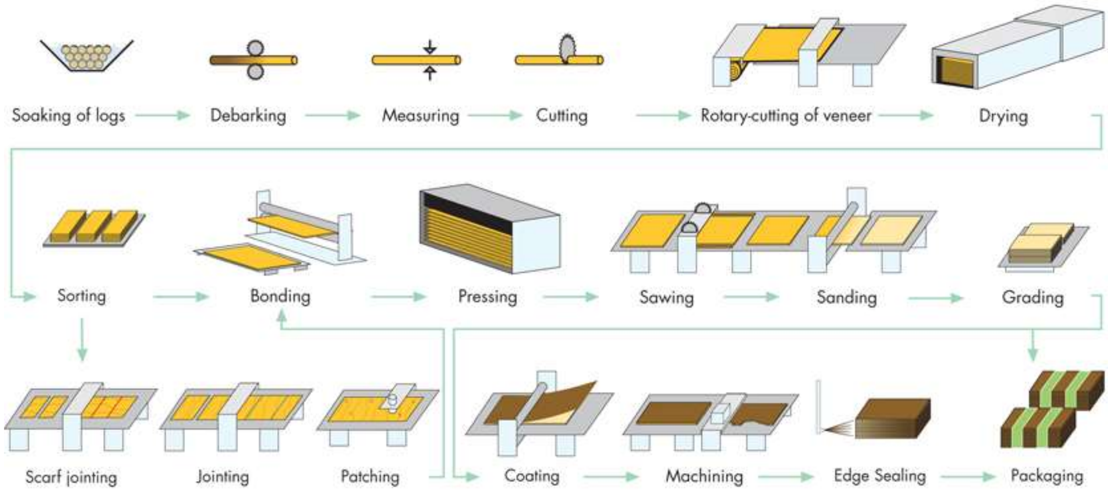


Figure 11 Plywood manufacturing process. (UPM-KymmeneOyj2015a)

The majority of plywood is glued with phenol-formaldehyde (PF) adhesives, which makes possible to use the product outdoors. Products for only indoor use can also be glued with urea-formaldehyde (UF) adhesives. Due to these adhesives, there are some volatile organic compound (VOC) emissions from plywood. Overlaid plywood (Figure 12) is manufactured by coating the surface with e.g. phenolic, paint or melamine films, which improve e.g. the moisture and wear resistance. Also embossing is widely used especially for the transport industry. (Metsäteollisuus ry 2001) There are very few genuinely new plywood products, but one to mention is the UPM Grada. It is plywood with a thermoplastic adhesive, which makes it possible to reform it from a plate structure. The furniture industry in particular has shown interest in the new possibilities of moulding plywood. (UPM Grada 2015)

Figure 12 Example of overlaid plywood with phenolic film coating. (EPS Poland 2015)

Plywood reacts to changes in moisture conditions by minor changes in its dimensions. The relative humidity makes the strength and elasticity properties decline, which is important to take into account especially when the product is under load. Permeability to moisture and water vapour is rather good, but is dependent on the moisture content of the plywood. When the moisture content rises the permeability also improves. Most plywoods can be used in temperatures between -200 ºC to 100ºC. The recycling of plywood is normally carried out by burning at over 700 ºC, so as not to form harmful combustion gases. (Metsäteollisuus ry 2001)

At the moment the market in Finland is recovering from the recession of 2009 and the current production is over 1 millionm³. The trend around the world is rising, the global production in 2013 being over 134 million m³. (Faostat 2013) A major share of the produced plywood goes to export. (Koponen 2002) The production goes mainly to building and transportation businesses, as roofs, floorings, vehicle interiors and concrete moulds. Also the furniture industry uses plywood to some extent, mostly as frames that are hidden in the end product. (Auvinen et al. 2002)

2.4.2 Particleboard

Particleboard, together with medium density fibreboard (MDF), is one of the most important raw materials of the furniture industry. In particleboard the woodchips are still visible to the naked eye and the distribution of the chips may vary from even, layered and oriented to totally random scattering. Particleboard is manufactured by combining wood chips with a binder and exposing it to heat and pressure, the process being depicted in Figure 13. The chips for particleboard are first dried in high temperatures to have low enough moisture content for gluing and then screened to have uniform mixture of chips. The sorting of the chips is done e.g. to surface and middle chips and it is also dependent on the quality demand of the end product. For indoor applications the adhesive used is mostly UF, and particleboards for bathrooms etc. have Melamine-Urea-Formaldehyde (MUF) or PF as the binder. (Koponen 2002)

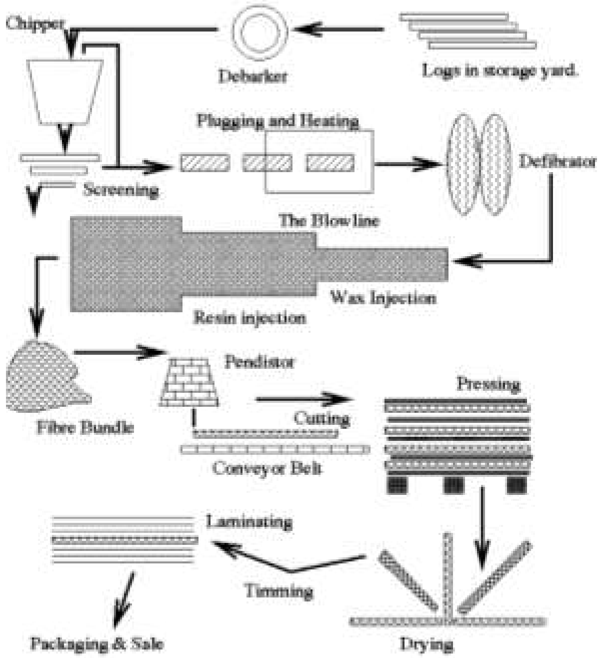


Figure 13 Particleboard manufacturing process. (McCallum, 1996)

The main advantages of particle board are its low price, manufacture from by-products and its tendency to swell uniformly in the direction of the surface without twisting. The downsides are that bending strength and stiffness of particleboards are low, which limits their use in structures that are subject to loads. (Auvinen et al. 2002) Particleboard is widely used in construction sites as separating walls, flooring, fixtures, claddings etc. (Figure 14) Due to its low price, many furniture parts are nowadays made of particleboard instead of solid wood. Also temporary structures such as fair stands or storages are often made of particle board. (Koponen 2002)

Figure 14 Particleboard with different coatings. (Alpha Particle Board Pvt. Ltd. 2015)

In Finland the manufacture of particleboard has shrunk to serve almost only the domestic market, which share is 88 % of the annual production of ~0,5 million m^3. This is used mainly in furniture industry, where it competes well against MDF. In Europe, production has grown to over 30 million m^3 with modern plants, which are close to market and have lower raw material cost than in Finland. (Merivuori & Koskinen 2009) As transporting of particleboard is not very feasible, Finnish companies lack competitiveness in foreign markets (Koponen 2002).

2.4.3 Fibreboard

Fibreboard is formed out of defibrated wood material i.e. the structure of wood is fiberized for the process. Many by-products, such as chips, sawdust, trimmings etc., can be exploited as raw material for fibreboard. The main advantage of fibreboard, compared e.g. to particleboard, is its easy processing due to its homogenous layered structure. This makes possible to make round edges, slotting, carvings etc. (Figure 15)

Figure 15 Different carved profiles of MDF sheets. (ErpaOrman 2015)

The most often used fibreboard type is MDF, but also low density fibreboard (LDF) and high density fibreboard (HDF) exist. Fibreboards are manufactured by mixing fibres with e.g. UF adhesive, exposing the material to heat and pressure and taking advantage of the natural adhesion feature of the fibres. Otherwise the process is similar to particleboard production (Figure 13). (Auvinen et al. 2002) One of the downsides of fibreboard is its tendency to absorb moisture and swell irregularly, which results in scattering of the structure and breakage of possible surface treatments. Also the bending strength and stiffness are low compared to larger particle wood products. (Fathollahzadeh et al. 2013)

Fibreboards are widely used in interiors and especially in kitchen furniture and in Europe e.g. MDF is available with thicknesses in the range of 1,8 to 60 mm. Moisture resistant, flame retardant, high density and exterior grades of MDF are available for use in more demanding situations. (EPF 2014) Currently MDF is not produced in Finland, but some hardboard manufacturers exist (Merivuori & Koskinen 2009). In Europe the current production is over 11,5 million m^3. (EPF 2014)

2.4.4 Wood-Plastic Composites

Wood-plastic composites (WPCs) can be roughly divided to two categories: WPCs with biodegradable plastics and WPCs with conventional plastics. The motivation to produce WPCs has many reasons e.g. the recycling of wood and plastic material, ecological values, improved durability, lower density etc. Often woods tendency to absorb moisture is also reduced and the use of toxic formaldehyde containing adhesives can be avoided.

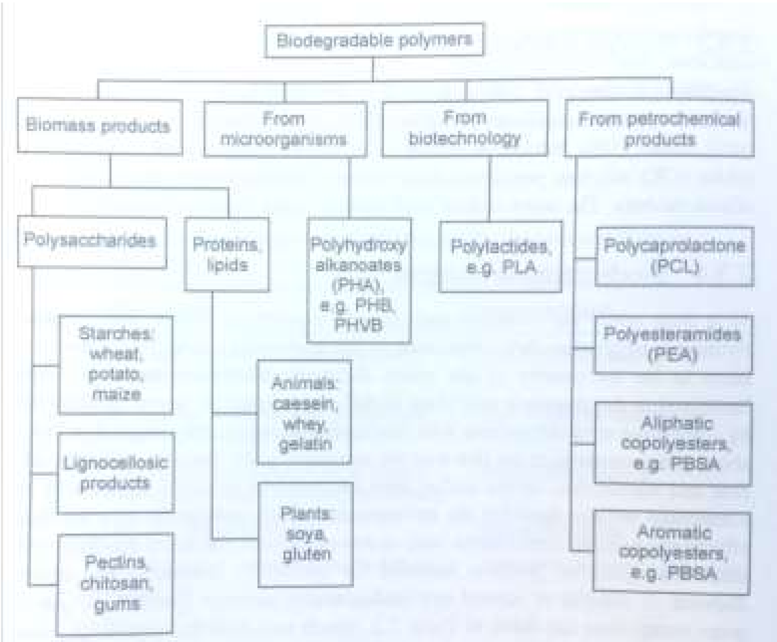


Figure 16 Classification of biodegradable polymers. (Averous & Boquillon 2004)

The main recycled plastics are PE and PP, although PVC has also been tried (Vinylplus 2014). The production of WPCs with biodegradable plastics is a growing trend to substitute conventional oil-based plastics and other energy intensive products. (Baillie 2004) There are numerous biodegradable polymers, which can be used when forming WPCs, some of them introduced in Figure 16. Both oil- and plant based polymers can be biodegradable. (Averous & Boquillon 2004)

One of the polymers derived from biomass is starch, which can be separated e.g. from potato or wheat. Thermoplastic starch is produced by destructuring the starch that converts semi-crystalline starch granules into an amorphous, homogeneous polymer. Often this is used to extend other polymers, creating a polymer blend. Polyhydroxyalcanoates (PHAs) are also acquired straight from natural origin, as they are linear polyesters produced by bacteria. (Baillie 2004)

The polymers derived from biomass can still be processed further. Poly-lactic acid (PLA) is thermoplastic polyester synthesized from lactic acid which is produced by the fermentation of dextrose obtained from starch. PLA is stable under many circumstances and degrades only in "composting" conditions. This is one reason why it is used widely in packaging, which will be discussed more later in this chapter. Polymers of petrochemical origin can also be biodegradable through chemical manipulation. Polycaprolactone (PCL) is derived from ε-caprolactone by a ring opening reaction which results in polymerization of the compound. It has a low working temperature of ~60 °C and it can be melted and reformed through several cycles before degrading significantly. Similarly to PLA, PCL also degrades under "composting" conditions. (Baillie 2004)

The most common ways to form WPCs are extrusion and moulding (Figure 17). The main difference between these methods is that in extrusion the matrix and the reinforcement are mixed during the process, when in moulding they are often mixed in advance. In extrusion the reinforcement is mixed with screws to the melted polymer matrix and forced through a die with desired cross-section. The beams of these cross-sections are then cut to length.

Figure 17 Typical extruded, injection moulded and compression moulded composite profiles. (Baillie 2004)

In moulding there are several different methods to force the material to the final shape. The most common method is injection moulding, where the melted composite is injected into a permanent mould, cooled down and taken out. In thermoforming the heated composite plate is pressed to form, cooled down and separated from the mould. Also in vacuum moulding the composite is heated up to its working temperature and then put under a vacuum on a negative or a positive mould. (Baillie 2004)

WPCs with conventional plastics are in commercial production especially in North America, where the main end use is in the decking market. Some applications for structural use and cladding are also available, but still a minor share. (Vinylplus 2014) In Europe the take-off has been slower, but e.g. UPM-Kymmene "ProFi" decking has been launched on the European market few years ago. The raw materials of "ProFi" decking are recycled paper and waste from self-adhesive label manufacturing. (UPM-Kymmene Oyj 2015b) In these uses WPCs replace e.g. treated timber products.

The packaging sector uses roughly 40 % of the global plastic production. Polymers used for packaging are relatively expensive and the role of natural-fibre reinforcement is to reduce the amount of polymer needed. Additional stiffness, strength, lightness etc. can also be achieved. Still, when conventional plastics are used, the recycling of the products is challenging, due to the large variety of different plastics. One solution to the recycling issue are biodegradable plastics. Especially PLA has become more popular in packaging as its costs have been reduced and it is competitive with the more expensive commodity thermoplastics such as PET (polyethylene terephthalate). The strengths of PLA include characteristics such as high strength, transparency and the possibility to alter the material from rubbery to glass-like. In addition to the recyclability, biodegradable plastics have potential in agriculture. Composting biopolymers can create a carbon rich soil and so reduce the need of fertilizing. (Duhovic et al. 2008)

A noteworthy user of the WPCs is the automotive industry, where door-liners, panels, parcel shelves, boot-liners etc. are made out of a variety of NFRCs. The use of different natural fibres, such as jute and hemp, results in a reduction in weight, carbon dioxide emissions and cost. The parts also become recyclable and producers are not so dependent on foreign oil sources (Holbery & Houston 2006). The use of WPCs is not only driven by the demand of ecologically aware customers at the market, but also by legislation. In Europe the European parliament has set a recyclability level of 85 % for automotive parts to be reached by 2015. (Directive 2000/53/EC)

The main objective in automotive manufacturing has been the change to lighter and non-toxic parts. Up to 40 % weight reduction in net vehicle weight can be reached with NFRCs compared to glass fibre parts. Not too many applications are used for exterior parts, as the requirements are more demanding for e.g. water uptake and fire resistance (Holbery & Houston 2006). Also the variation of fibre properties and the natural-fibre prices limits the use for exterior parts.

Figure 18 A) Imprint chair (Lammhults Möbel AB 2015) B) Kupilka Outdoor dining vessel (Plasthill Oy 2015) C) Flaxwood guitar (Flaxwood 2015) D) Art piece made of Woodn composite material (Woodn Industries Srl 2012).

Some new inventions for exterior use of NFRCs are in testing phase e.g. at Daimler-Chrysler and Mercedes-Benz (Huda et al. 2008). UPM has also its own Biofore Concept Car –project, the objective of which is to design and manufacture a sustainable development car for the urban environment. The Biofore Concept Car was introduced at the Geneva International Motor Show 2014. (UPM 2014) Other markets for WPCs can be found in art, cutlery, furniture and even music (Figure 18). Although these are mostly niche products compared to e.g. automotive industry, they have a huge potential of renewal in their own field.

2.4.5 Nanocellulose Reinforced Composites

Nanoscale applications are constructed in the dimension of 1-100 nm (10^{-9}m), where modification on molecular level is possible. While considering nanocellulose applications, cellulose is often modified to inter alia alter its hydrophobic nature. Different treatments, such as acetylation, silylation or polymer grafting, can be also performed to functionalize the cellulose surface. (Bulota 2012) Crystalline cellulose whiskers for reinforcing are mainly in the range of 2-20 nm. (Newman & Staiger 2008)

Functionalized cellulose can be used in many forms (e.g., powder and aerogel) and it has a wide range of applications from food additives to binders (Bulota 2012). Choosing a suitable resin to mix with these cellulose nanofibres is crucial, as the resin must be capable of penetrating the nanoscale pores. One way to accomplish this is to dilute the resin with a solvent and evaporate it after mixing. After evaporation the composite can be hot-pressed to form films. One special advantage of nanoscale cellulose composites is their transparency, as the particles are so small that they do not scatter light. (Newman & Staiger 2008)

Jung et al. (2015) have manufactured a CNF film with high transparency, flexibility and good electrical properties to be used in electronics. The potential of the product is in microchips (Figure 19), which often contains toxic compounds. As CNF are wholly wood-based and biodegradable, they can reduce the amount of harmful components. (Jung et al. 2015)

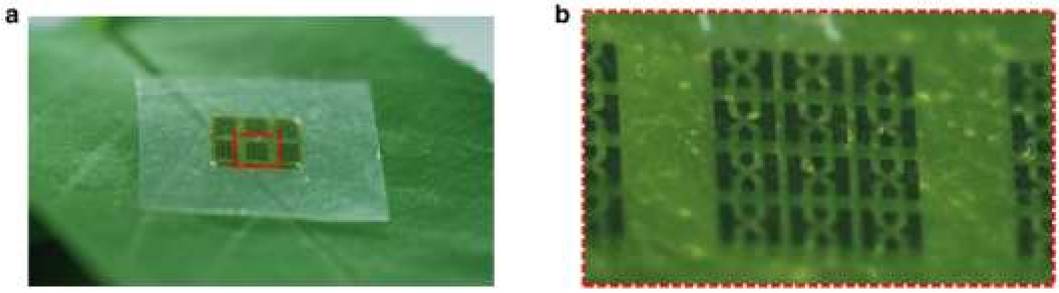


Figure 19 Microwave active GaAs electronic devices on CNF paper. (Jung et al. 2015)

Obstacles for the wider use of nanocomposites are numerous. The costs of the processing steps are high and the production needs large volumes of processing water. Cellulose nanofibres do not bring big advantages in modulus and strength, but on the other hand the fibres can contribute to other properties e.g. toughness (Newman & Staiger 2008).

2.5 Woodcast® Composite Material

The material is highly adjustable due to its composite nature. By choosing different processing methods and composition of the plates, the appearance, durability, stiffness and surface properties can be altered to meet the desired characteristics. The composite is self-adhesive and adheres easily to other porous materials such as cotton wool. Also the raw material selection plays an important role and enables inter alia the alteration of moulding temperature.

2.5.1 Technical Properties

The numerical values for Woodcast® can be found in Table 1. Strength is the stress at ultimate load i.e. the point where the material fails. In bending 4 mm thick Woodcast® plate follows Hooke's law with forces under ~4,8 MPa i.e. until the load reaches the elastic limit (Figure 20).

Table 1 Woodcast®'s properties. (Pat. WO 2010/103186 A2, Muovipoli Oy 2011, Appendix 1: Tensile properties of Woodcast®, Appendix 2: Water absorption properties of Woodcast®)

4 mm Woodcast®	
Bending strength	17,47 Mpa
Bending modulus	970,61 Mpa
Tensile strength	10,38 Mpa
Tensile modulus	1250 Mpa
Density	600-850 kg/m³
Melting point	65 °C
Particle size	1-3 mm
Volume swell (24h)	5,28 %
Elongation at break	1,79%

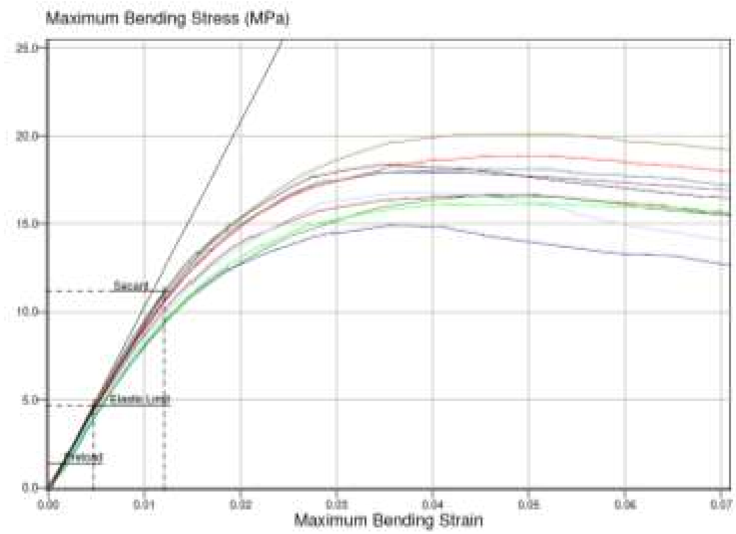


Figure 20 Stress-strain curves of Woodcast® in 3-point-bending test. 10 test specimen. Elastic limit is also known as yield point. (Muovipoli Oy 2011)

2.5.2 Previous Studies

The material properties of the Woodcast® were analysed in studies of Leiniö (2014) and Pirhonen et al. (2012). The stiffness properties of Woodcast® were analysed and compared with conventional casting materials. Woodcast® performed very well by obtaining equally high stiffness with fibreglass and not showing any marks of delamination under stress. The stiffness of the product is a significant factor in safe fracture immobilization. (Pirhonen et al. 2012) The natural aging and durability was measured in the paper of Leiniö (2014) over a four year period. The cast material was stored under the controlled atmosphere of +23 ±2 °C and 50 ± 5 % RH at the Muovipoli Oy laboratory. The results show, that no notable degradation of the material has occurred during four years of storage. (Leiniö 2014)

2.5.3 Other Properties

Woodcast® has also many properties worth mentioning, which do not fall into the categories presented above. The edge jointing of the material is relatively easy: to acquire a tight joint it only needs to be overlapping by 1 cm from the edges and heated over 100 °C. It is easier to edge joint 4 mm than 2 mm thick plates of the material. If the joint is hot pressed the seam will get invisible.

As the material has pleasing haptic properties, it has potential in surfaces which are touched by users. Also the natural look of the material supports usage in consumer products. All the plastic components in the material are in accordance with the EU-directive 2002/72/EC i.e. they are allowed to be in contact with groceries. These points connected with the ecological and biodegradable features of Woodcast® make it a high-end product feasible for also transporting. The safety of Woodcast® -products is tested in accordance with ISO 10993 –standard’s biological tests. In these tests the material did not show any biological response and so it can be situated in the lowest risk class. (Onbone Oy 2014)

2.6 Woodcast® in Comparison to other Composites

Table 2 introduces some examples of different composite types and their characteristics. Also one biodegradable plastic, Terratek BC 4015, is included for comparison to all-plastic products. Nanocomposites discussed in section 2.4.5 are not included in the comparison, as they are rather used as coatings, than as plates.

Table 2 Examples of different materials compared to Woodcast®. a = 4 mm thickness, b = perpendicular to grain, c = Greenwood® Deck, d = Terratek BC 4015, e = surface chips; core chips 0,4-0,7 mm, f = typical fibre dimensions approximately: length 3,0 mm and width 30µm for softwoods, length 1,0 mm and width 16 µm for hardwoods, g = 72 h immersion (Pat. WO 2010/103186 A2, Muovipoli Oy 2011, Appendix 1: Tensile properties of Woodcast®, Appendix 2: Water absorption properties of Woodcast®, Metsäteollisuus ry 2001, EWPAA 2008, Koponen 2002, Greenwood SRL 2011)

	Bending strength	Bending modulus	Tensile strength	Tensile modulus
Woodcast® 4 mm	17,47 MPa	970,61 MPa	10,38 MPa	1250 MPa
Birch plywood[a]	10,6 MPa[b]	1029 MPa[b]	29,2 MPa[b]	6806 MPa[b]
Spruce plywood[a]	6,0 MPa[b]	765 MPa[b]	10,9 MPa[b]	5056 MPa[b]
PB (≤ 9mm thick)	18 MPa	2800 MPa	-	-
MDF[a]	44 MPa	3800 MPa	-	-
WPC[c]	29 MPa	3900 MPa	20 MPa	4600 MPa
Biodegr. plastic[d]	-	-	18,6 MPa	-
	Density	Melting point	Particle size	Thickness swell (24h)
Woodcast® 4 mm	600-850 kg/m³	65 °C	1-3 mm	4,97 %
Birch plywood[a]	700 (± 50)kg/m³	-	large (veneer)	0,3-0,4%
Spruce plywood[a]	460 (± 50)kg/m³	-	large (veneer)	0,3-0,4%
PB (≤ 9mm thick)	660-700 kg/m³	-	0,2-0,3 mm[e]	15 %
MDF[a]	800-850 kg/m³	-	fibrous[f]	20-30 %
WPC[c]	1170 kg/m³	-	-	4,5%[g]
Biodegr. plastic[d]	1300 kg/m³	190 °C	-	≤ 1 %

The values for plywood, particleboard and MDF are for generic products, thus basic products should fill these requirements. The wood-plastic composite included in the Table 2 is Greenwood® Deck, a profiled decking material. It consists of 15% to 70% of wood dust or fibre and at least one of the following polymers: PVC, PP or PE and is covered with a transparent thermoplastic polymer film. (Greenwood Srl 2011) The plastic Terratek BC 4015 is a blend of natural and synthetic biodegradable polymers and it represents the properties of a merely plastic composite material.

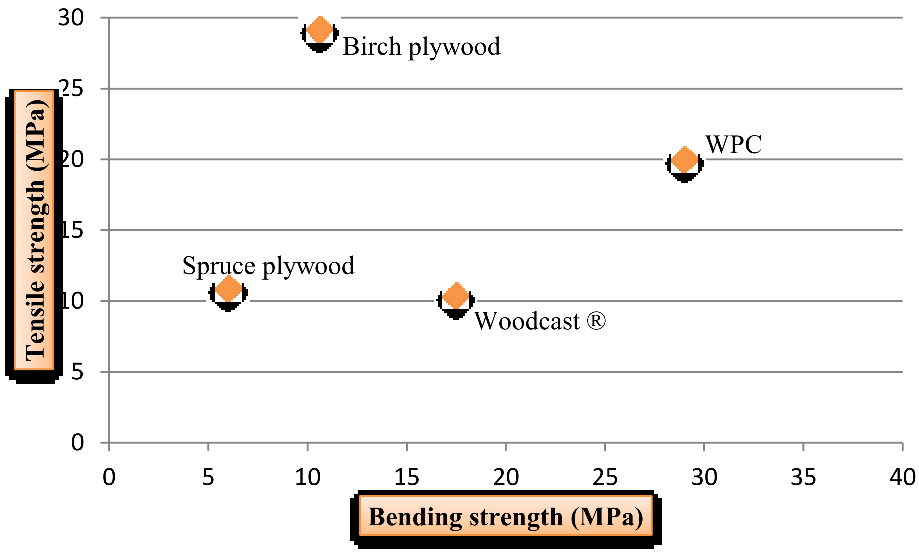


Figure 21 Comparison of tensile strength and bending strength of the materials in Table 2.

It can be seen in Figure 21 that Woodcast® performs well in bending strength compared to plywood. The WPC used in the comparison (Greenwood® Deck) did not have values for 4 mm thick plates, so the values are general and not directly comparable. Tensile strength of 4 mm Woodcast® is in the same range with 4 mm spruce plywood, which makes it interesting to investigate possibilities of replacing plywood with Woodcast®.

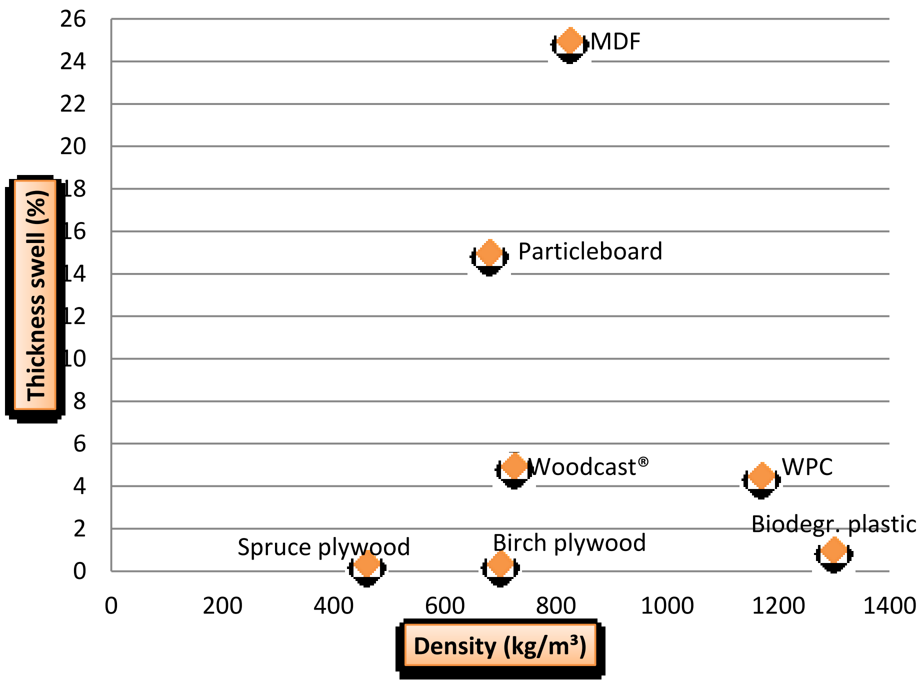


Figure 22 Comparison of thickness swell and density of the materials in Table 2.

In comparison to particleboard and MDF in the same density range, Woodcast® has really low thickness swelling. It cannot compete with the stability of plywood or mere plastic, but with the denser WPC the difference in swelling is negligible. (Figure 22) There were no data available about elongation at break for all of the products compared in Table 2, but it is worth mentioning that the WPC had a 0,98 % elongation at break and the value for Woodcast® is 1,79 % (Appendix 1, Table A1-1). This shows that Woodcast® is obviously more adaptable than the WPC, but a wider comparison is needed for a definite conclusion.

A directly competing biodegradable product for Woodcast® could not be found in WPCs. To get a glimpse of the properties of biodegradable composites, the biodegradable plastic was included in the comparison. If the inspection would be extended to other bio-based composites containing e.g. flax, jute or kenaf, potential competitors might emerge. Nevertheless, in the light of this comparison Woodcast® possesses such properties that it is highly competitive with existing products.

3 Experimental Part

In the attempt to identify feasible applications for Woodcast®, both qualitative and quantitative research methods were used. Quantitative research of tensile strength, water absorption and mouldability was firstly conducted to acquire data for product comparison and secondly to gain new information of the product characteristics (see section 3.2). Nevertheless, the weight of the research was on qualitative methods.

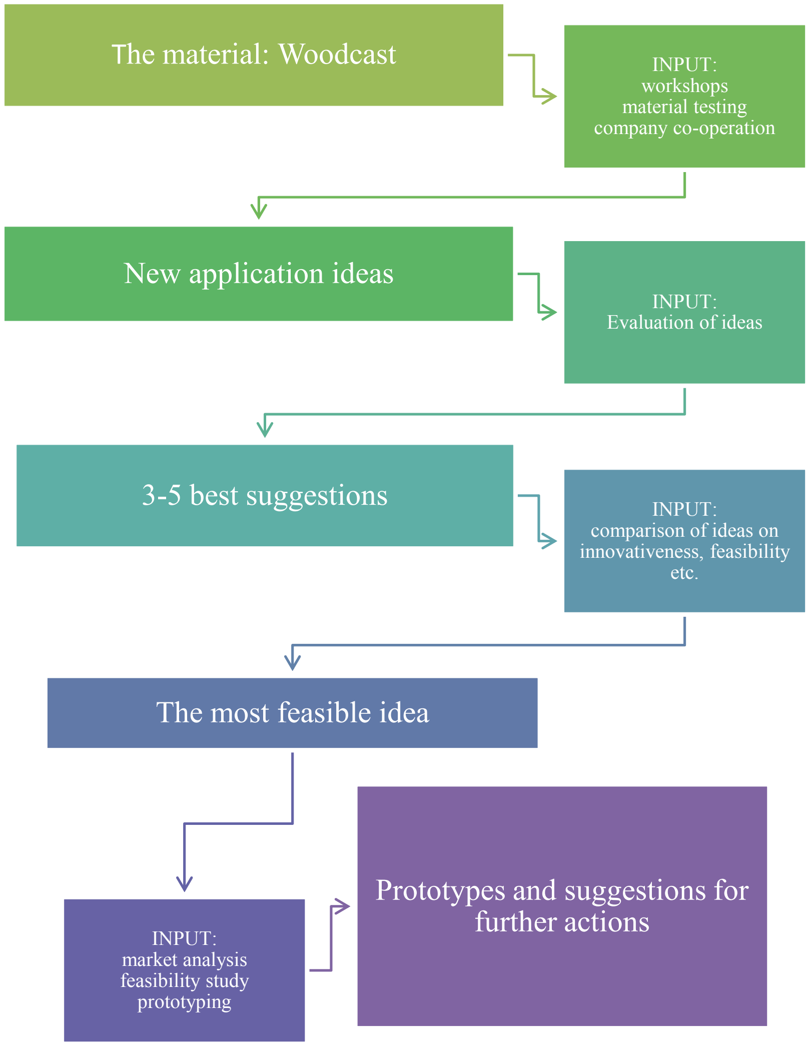


Figure 23 The flow of the experimental work throughout the thesis.

The qualitative data was gathered through interviews, workshops, literature etc. by applying the techniques of design thinking, which is introduced in section 3.1. The ideas drawn were evaluated according to the product development process in "Product Design and Development" by Ulrich and Eppinger (2000) and the best ones then taken to closer investigation. The further inspection of the chosen ideas included a short feasibility study, prototyping and recommendations for further actions. (Figure 23)

3.1 Qualitative Methods

3.1.1 Design Thinking

The process of generating new uses for Woodcast® included ideas of the company, colleagues, friends and experts with research of literature and internet. This was accompanied with own ideation and qualitative testing of the material. To systematically map these new possibilities for the material, the techniques of design thinking were applied.

The core of design thinking comes from the idea that designers are thinking like business people and vice versa. On the other hand, it cannot be described precisely as it evolves from project to project. As Mootee (2013) wraps up: “Design thinking is its own mode of analysis – one that focuses on forms, relationships, behaviour, real human interactions and emotions.” In this thesis cognitive flexibility was considered as an important factor: How well the process is adaptable to changes and challenges on its way? Social innovation was used in the form of workshops to have problem solving from the end user perspective and finding unmet needs.

In our modern society data is produced at such amounts and speed that it results in data paralysis – we cannot give attention to all of it, which makes decision making increasingly challenging. In the light of this project the core question is: What people expect from a product like Woodcast®? Data of the physical properties of the material is gathered through testing, but as mentioned by Mootee (2013), data is no substitute for intimacy. Customers need to see, touch and experience the product and have the human interaction to make a positive image of the product. This brings us to the point that a big part of design thinking is design doing, taking yourself out on the field and trying out possible solutions.

Design thinking has in principle six phases: define, research, ideate, prototype, implement and learn. In the beginning of a design process the issue, the audience and keys to success are the most crucial themes to define. The research can then be based on these themes, so that previous attempts and obstacles are mapped and end-users’ opinions taken into account. When the background is clarified, the ideation can be initiated on the grounds of needs and motivation, but also leaving space for brainstorming and intuition.

Ideation is followed by prototyping phase, where the ideas are refined and tested. The result of prototyping should be a set of feedback for improvements and guidelines for implementation. As the implementation phase takes place, the task for the product or service needs to be defined and clearly described, so that the last phase, learning, can take place. Learning is probably the most important phase in the loop as it makes the process start over again and forms an iteration loop, which does not let the development stagnate. Learning in the design thinking process should include at least consumer feedback, success measurements and analysis of the goals met. (Mootee 2013)

3.1.2 Workshop

Workshop was chosen to be one of the ways to map different possibilities for Woodcast® as the typical way of working for a designer is material oriented. The restrictions and possibilities of the material need to be taken into account during the design process. Hands-on work and the physical nature of design are important parts of the design process and different kind of ideation methods during a workshop are tools for the design process. Working in a group is an essential component of the designer's work: introducing own ideas and the working process to others helps with the observation of one's own ideation structures. (Leinonen 2014)

The workshop consists of two parts: a preliminary meeting with the group where the product is demonstrated and the actual workshop with feedback e. g. a week later (Figure 24). In the preliminary meeting there is an approximately 30-minute introduction of the product and an in practice example of the product's characteristics. In addition a small task (Appendix 3) is given as preparation for the practical part.

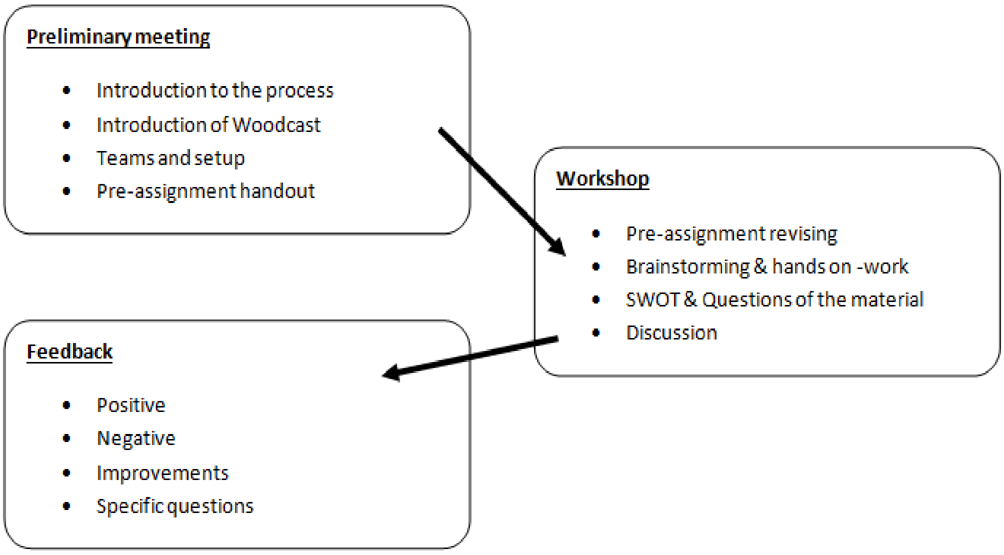


Figure 24 Workshop structure.

The actual workshop has three parts: Brainstorming for new applications based on the pre-task, hands on work in teams and wrap-up discussion with the whole group (Appendix 4). In the beginning the group is divided to teams and given instructions and a form to fill in for the workshop (Appendix 5). The analysis of the workshop is then based on these forms and the discussions held during the workshop.

3.1.3 Evaluation of Possible Applications

The product development process used in this research is extracted from the title "Product Design and Development" by Ulrich and Eppinger (2000) and applied to the issue under investigation. The guidelines of the title gave the base for weighing and comparing different options. The process of finding and evaluating possible applications for Woodcast® included the following phases:

1) Concept generation
2) Concept selection
3) Deeper analysis of the best concept ideas and
4) Concept testing (to be done in the future).

Concept is an approximate description of the technology, working principles and form of the product. To get started with the development of a concept, all possibilities which come in mind are collected, ending up with up to 100 ideas. This listing is then observed to rule out ideas which are not applicable even in theory.

When the amount of ideas is screened, internal and external search take place. Internally this means using the personal and colleague knowledge to gather information for the further development of the concept. External search then includes benchmarking, interviews and workshops to find out who are the actors in the concept's field. According to the findings from the previously mentioned methods, the possibilities are explored systematically, in this case using a concept classification tree, before proceeding to concept selection (Ulrich & Eppinger 2000).

The concept selection phase consists of several methods including intuition, pros and cons, rapid prototyping (see Section 3.2.4) and initial testing. At this stage concept benchmarking is also done. The two-stage methodology in this phase includes first concept screening (Table 3) and then concept scoring (Table 4). The process aims to cut down the number of possible applications, so that it is possible to concentrate on the most viable ones. Another advantage of the methodology is that there is documentation of the design process to be archived for future projects.

Table 3 Model of the concept screening matrix, generated according to methods introduced by Ulrich & Eppinger (2000).

	Concept screening matrix				
	Pros	**Cons**	**Score**	**Continue?**	
Concept 1	feature 1a + feature 1b +	feature 1c -	1	YES	**advantage +** **major advantage ++**
Concept 2	feature 2a ++	feature 2b -- feature 2c -	-1	NO	**drawback -** **major drawback --**
Concept 3	feature 3a + feature 3b ++	feature 3c -- feature 3d -	0	YES	**If score is < 0, concept is ruled out.**
Concept 4	feature 4a +	feature 4b -- feature 4c -	-2	NO	
Concept 5	feature 5a + feature 5b +	feature 5c -- feature 5d -	-1	NO	

As seen in the model concept screening matrix (Table 3), each concept is observed for major features – both for drawbacks and advantages. To cut down the amount of concepts radically, all concepts with a score below zero will be excluded. The remaining concepts are then inserted to a concept scoring matrix (Table 4), where they are scored according to 4-10 weighed criteria. The scale for scoring is from 1 to 5. Total score is calculated as an arithmetic mean of the criteria and the weighed score according to the weights set for each criterion.

Table 4 Model of the concept scoring matrix, generated according to methods introduced by Ulrich & Eppinger (2000).

	Concept scoring matrix				
	Concept 1	**Concept 2**	**Concept 3**	**Concept 4**	**Weight ***
Criterion 1	1	2	4	3	**10 %**
Criterion 2	2	2	4	3	**20 %**
Criterion 3	1	2	3	5	**30 %**
Criterion 4	3	4	1	2	**40 %**
Total score	1,75	2,5	3	3,25	
Weighed score	**2**	**2,8**	**2,5**	**3,2**	

*** = Weight of each criterion from total of 100 %**
Criteria are evaluated with a scale of 1-5, where 1 is the worst and 5 is the best value.

The concept scoring matrix gives guidelines for picking the best suggestions for deeper analysis. Depending on the amount of concepts observed 1-3 options are chosen. The amount is such that the options can be thoroughly scanned in a reasonable time frame. Some concepts may be such that they can be combined, which should be taken into account in all the phases. (Ulrich & Eppinger 2000)

The last concept(s) left will be analyzed through a market analysis, benchmarking and a short feasibility study. First prototypes are made, if it is possible, but the iteration cycles are yet to be done in the future. Especially “material in use” observations should be made later in the process as it links closely to customer or user responses and opinions of the product.

3.1.4 Prototyping

The prototyping for the thesis was committed in two ways: in workshops and as personal testing e.g. the vacuum moulding experiment (see Section 3.2.3). The base idea used for the prototyping in both ways was experience design combined with elements from rapid prototyping adapted from “Design thinking for strategic innovation: what they can't teach you at business or design school” by Mootee (2013). The base concepts of prototyping are presented according to Ulrich & Eppinger (2000).

Prototypes are generally classified in four dimensions: physical, analytical, comprehensive and focus prototypes (Figure 25). Physical prototypes serve often the “proof-of-concept” –mentality as analytical prototypes, e.g. computer simulations, are used for calculations and technical information for the developers. The focus prototypes serve as pieces of the puzzle for the developers: it is often easier to form a “looks-like” and a “works-like” prototype than get all the functionalities together at once. When these focus prototypes are combined they result in a comprehensive prototype for the end user. (Ulrich & Eppinger 2000)

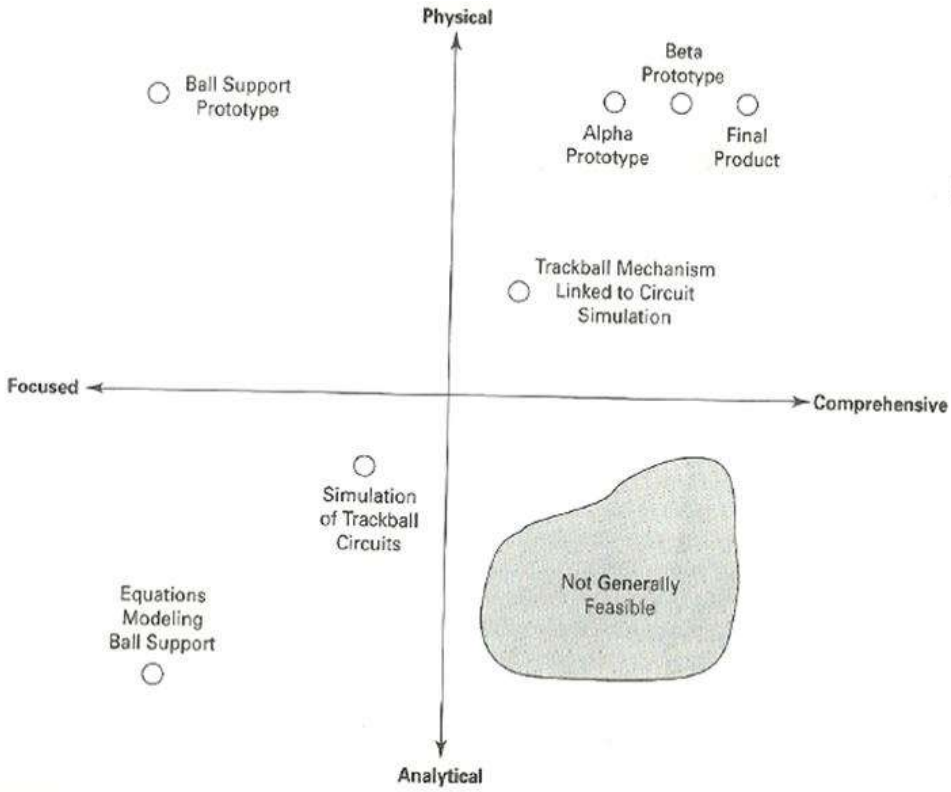


Figure 25 Types of prototypes. (Ulrich & Eppinger 2000)

There are four purposes for prototypes in a product development project: learning, communication, integration and milestones. Learning and communication concentrate mostly in social aspects linked to the product. The essence of learning is the question “Will it work?” which eventually drives the process further to investigate customer needs and other areas of improvement. Communication is part of the learning process as a concrete 3D-model is much easier to understand for all the stakeholders, such as top management, extended team members and customers. When the issue is understood properly, it is easier to receive an appropriate feedback. (Ulrich & Eppinger 2000)

Integration and milestones bring structure to the development process. In integration bringing together all the components, to see if some of them are interfering with the overall function of the product, will very probably reduce time of development and the number of iteration cycles needed. Milestones have large impact in the later stage of product development as the prototypes demonstrate progress and goals achieved. The documentation of the whole process supports the development and may even help to detect unanticipated phenomena (Figure 26). (Ulrich & Eppinger 2000)

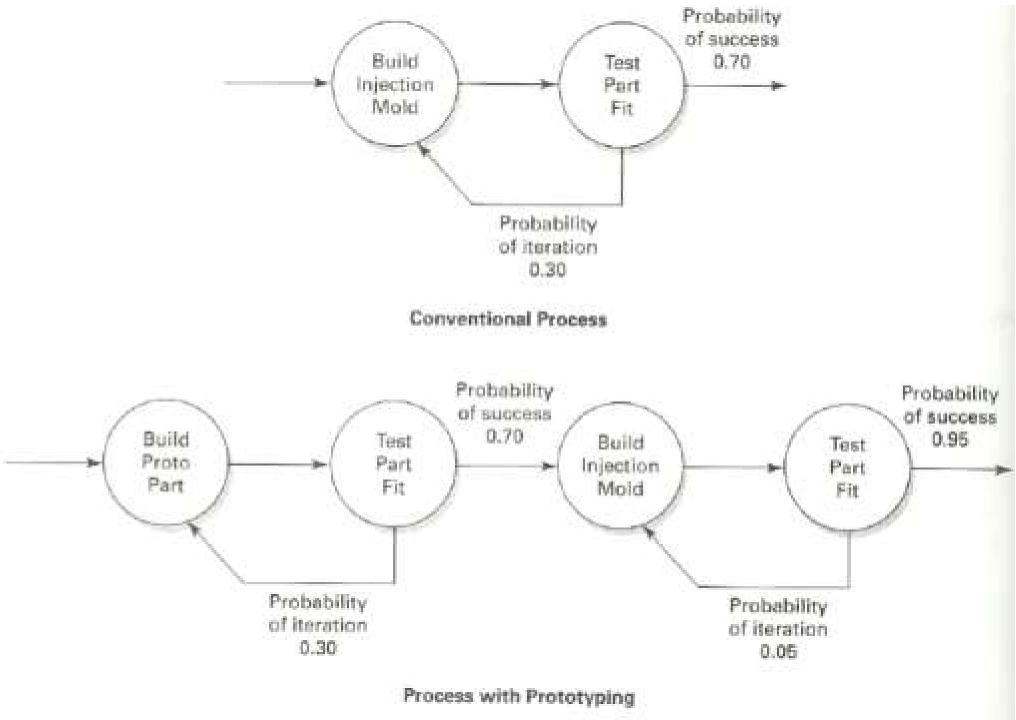


Figure 26 Prototype’s effect on iteration process. (Ulrich & Eppinger 2000)

The prototypes do not appear by themselves, but they need designers and developers. Experience design is based on the sensation of interactions with a product or service on physical and cognitive levels. One of the main questions there is: How the product communicates meaning and intent? Experience design uses concrete materials and tries to find both emotional and functional values. At the same time expectations and assumptions are gathered to find out how the end user sees the product or service. To get the most of experience design one must determine the scope and understand the intensity of the experience, identify the experience triggers and deepen engagement to evoke meanings. Advantages found with experience design might e.g. find new emotional elements which add value but not the production or other costs. (Mootee 2013)

Closely engaged with experience design comes rapid prototyping. It is an iterative learning process of build, see, test and refine or in other words “Learn fast, learn cheap, learn early”. Rapid prototyping is relatively low-cost hands-on activity for finding design and development risks early and which can engage and involve several stakeholders at the same time. As anyone can prototype, the concept of rapid prototyping is an agile tool to use whenever in the design process from paper to the final product. Multiple feedback loops make the ambiguous concepts more tangible. (Mootee 2013)

3.2 Quantitative Methods

To get a holistic view of the properties previous research was studied and further research of the material properties was conducted with tensile strength and water absorption tests according to standards ISO 527-4:1997 and ISO 62:1999, respectively. Vacuum moulding was also prototyped with three specimens for initial comparison with other mouldable products.

3.2.1 Tensile Strength

The tensile strength test was committed with 4 mm and 2 mm thick Woodcast® plates using Instron Universal Testing Instrument Model 33R4204 with a 5 kN load cell. There were 12 rectangular specimens (ISO 527-4:1997 Type 2), of which 1 was excluded, with dimensions of 4mm x 400mm x 25mm and 10 rectangular specimens (ISO 527-4:1997 Type 2) with dimensions of 2mm x 340mm x 25mm (thickness x length x width).The specimens were stored in 23 ºC and 50 % RH for a week and the measurements were done in the same conditions. The grip distance in the test was 50 mm and the testing speed was 10 mm/min. The specimen appearance and test setup is depicted in Figure 27. The results are found in section 4.1.

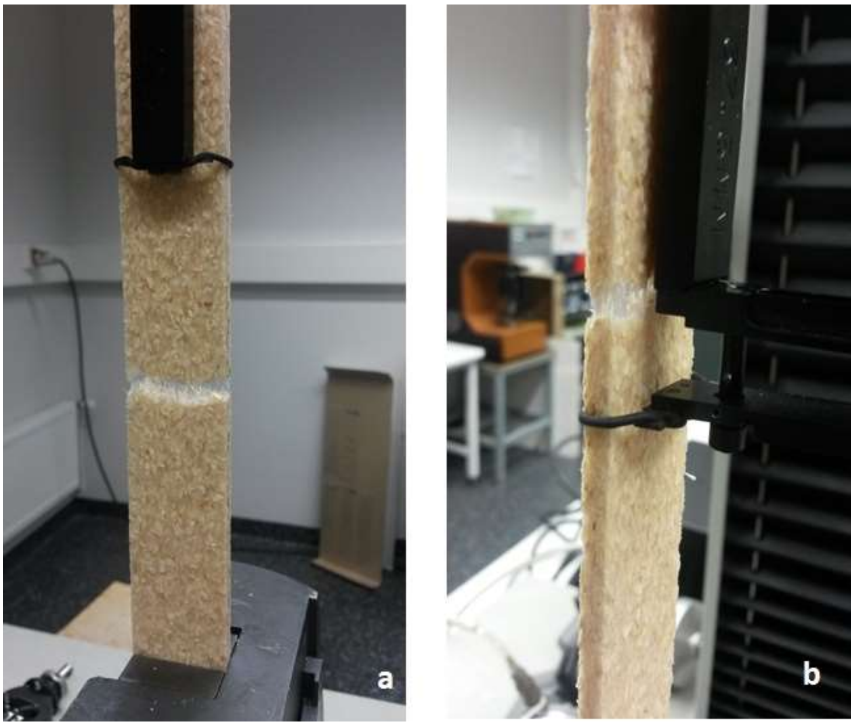


Figure 27 a) The test setup with rupture of the specimen. b) The test setup with rupture within extensometer gauge.

3.2.2 Water Absorption

The water absorption properties of the material were tested according to the standard ISO 62:1999. All the specimens were dried in 50 ºC for 24 hours and let to cool down in desiccators in 23 ºC. Two batches were tested; one in 22 ºC and the other in 70 ºC distilled water immersion for 24 hours. Both batches had specimens of 4 mm, 2 mm and 2 mm soft, 10 pieces each. The specimens were squares with dimensions of (61±1) mm x (61±1) mm. The results are found in section 4.2.

3.2.3 Vacuum Moulding

The vacuum moulding experiment was committed with a vacuum device combined with a silicon film. The 2 mm and 4 mm thick test samples were initially heated up in an oven to approximately 65 °C and then placed between the plate and the silicon film with a test mould underneath (Figure 28). Then the vacuum was formed and the samples let to cool down before opening the device.

Figure 28 2 mm thick samples in the vacuum moulding device at Aalto University School of Arts, Design and Architecture, Helsinki.

4 Results and Discussion: Quantitative Evaluation

4.1 Tensile Strength

The values derived from the tensile strength test results were the Young's modulus (Figures 29 and 30), tensile stress at yield and tensile strain at break (Figure 31). These values are found in Appendix 1. The arithmetic mean of Young's modulus for 4 mm specimens was $\overline{x}$ = 1250,1 MPa and the standard deviation was σ = 105,2 MPa, and for 2 mm specimens the arithmetic mean was $\overline{x}$ = 1844,0 MPa and the standard deviation was σ = 105,3 MPa. The arithmetic mean of elongation for 4 mm specimens was $\overline{x}$ = 1,79 % and the standard deviation σ = 0,17 %. The arithmetic mean for 2 mm specimens was $\overline{x}$ = 1,66 % and the standard deviation was σ =0,22%.

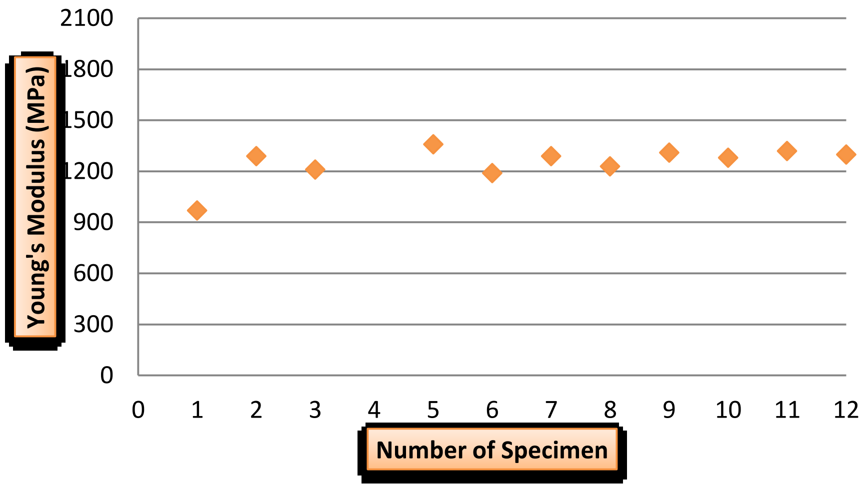


Figure 29 Young's modulus of 4 mm thick Woodcast® specimen, values found in Appendix 1. For specimen 1.4 no valid data were acquired.

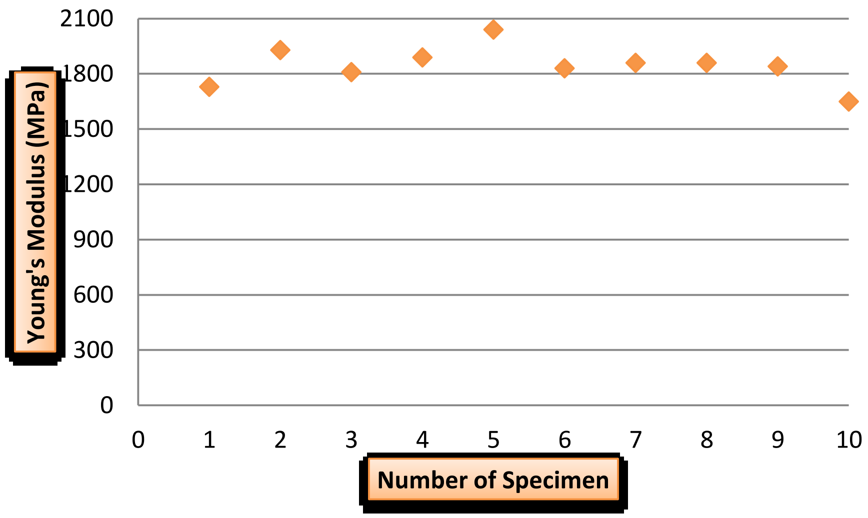
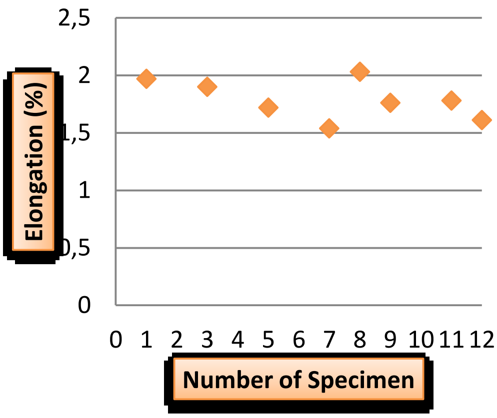


Figure 30 Young's modulus of 2 mm thick Woodcast® specimen, values found in Appendix 1.



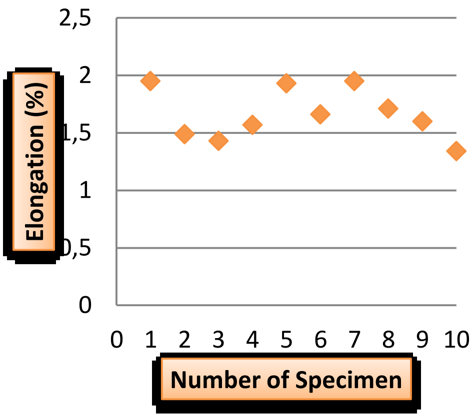


Figure 31 Left side: Elongation of 4 mm thick Woodcast® specimen, values found in Appendix 1. Specimen 1.2, 1.4, 1.6 and 1.10 are excluded due to breakage within the extensometer gauge. For specimen 1.4 no valid data was acquired. Right side: Elongation of 2 mm thick Woodcast® specimen, values found in Appendix 1.

In specimens 1.2, 1.4, 1.6 and 1.10 the breaking point was within extensometer gauge and thus the elongation could not be measured (Figure 32). Specimen 1.4 was loaded with wrong parameters, so valid data could not be acquired. In addition the specimen 1.1 had only 1 kN load cell, which was changed to 5 kN load cell for the rest of the samples. It should be mentioned, that the 4 mm plates were from an older batch than the 2 mm plates and the storing time might have affected their properties.

Figure 32 Specimen 1.1 to 1.12 after testing, thickness 4 mm. Breaking point within extensometer gauge: 1.2, 1.4, 1.6 and 1.10.

4.2 Water Absorption

In the initial drying of the water absorbance test the change in masses and volumes for all samples (1-60) was negligible, as the moisture content of the samples was already low (Tables 5 and 6). The measurements show that after 22 °C water immersion the average change in volume was 8,5 % (standard deviation σ = 2,8 %) for 4 mm, 5,3 % (σ = 3,1 %) for 2 mm and 8,2 % (σ = 3,2 %) for 2 mm soft samples.

Table 5 Water absorption test average values for volume, mass and density changes in 22 °C water immersion. The measured values are found in Appendix 2.

		after drying			22 °C	after soaking		
Samples	Type	Average ΔV1 (%)	Average Δm1 (%)	Average Δρ1 (%)		Average ΔV2 (%)	Average Δm2 (%)	Average Δρ2 (%)
1-10	2 mm	0,924	-1,000	0,002		8,453	8,637	-0,548
11-20	4 mm	0,790	-0,601	0,209		5,280	4,517	-0,759
21-30	soft	0,866	-1,031	-0,099		8,226	7,746	-0,869

The average change in masses followed the same trend with values of 8,6 % (σ = 0,4 %) for 4 mm, 4,5 % (σ = 1,36 %) for 2 mm and 7,7 % (σ = 1,7 %) for 2 mm soft samples. The density remained relatively stable in all types of samples. (Table 5) The deformation of these samples was mild, most of them bending slightly towards the upper surface i.e. towards the side where the slits had been made (Figure 33).

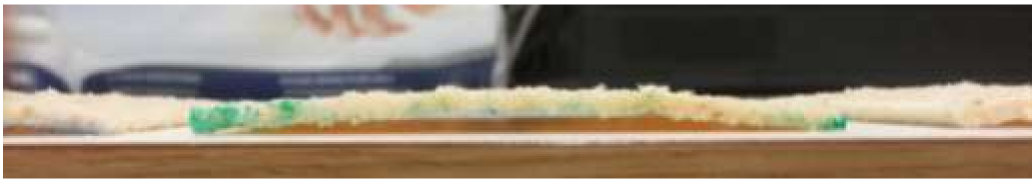


Figure 33 Bending of the 2 mm specimen after soaking.

The measurements show that after 70 °C water immersion the average change in masses was 88,3 % (σ = 6,2 %) for 4 mm, 92,7 % (σ = 6,4 %) for 2 mm and 87,5 % (σ = 5,8 %) for 2 mm soft samples (Table 6). The density and volume changes could not be recorded as the samples became so deformed and partly adhered to each other (Figure 34). The 2 mm and 4 mm samples' water turned yellowish and had a noticeable odour.

Table 6 Water absorption test average values for volume, mass and density changes in 70 °C water immersion. The measured values are found in Appendix 2. * = no data, because the soaked samples were not measurable.

		after drying			70 °C	after soaking		
Samples	Type	Average ΔV1 (%)	Average Δm1 (%)	Average Δρ1 (%)		Average ΔV2 (%)	Average Δm2 (%)	Average Δρ2 (%)
31-40	2 mm	-0,1463748	-1,10828	-0,01163		*	88,32995	*
41-50	4 mm	1,5364083	-0,69685	0,012776		*	92,77649	*
51-60	soft	2,4674357	-1,14247	0,011506		*	87,51435	*

Figure 34 Swelling of the 4 mm specimen after soaking.

The 4 mm thick samples (41-50) were the least deformed, so they were dried once more to see if the swelling would be reversible. The result was that the dimensions did not recover, but the structure remained porous. (Figures 35 and 36) This phenomenon was probably due to the presumption that the plastic is not impregnated in the wood particles. As 70 °C water was applied the plastic cover of the wood particles melted and water was free to enter the wood. In both batches it was noticeable that the samples swelled more perpendicular to the slits than along them (Figure 35).

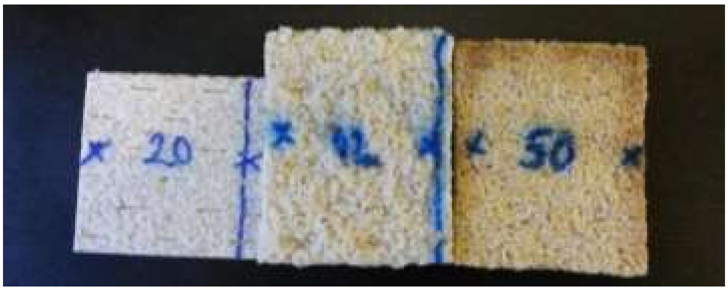


Figure 35 4 mm specimen from the 70 °C batch before soaking, after soaking and after drying, respectively from left to right.

Figure 36 4 mm specimen from the 70 °C batch before soaking, after drying and after soaking, respectively from the bottom to the top.

4.3 Vacuum Moulding

The material replicated the different mould shapes excellently, including the corners and the texture of the mould. The slits closed up during the moulding. Low working temperature and the possibility to remodel the samples were found to be advantages for the material when compared to other materials used in vacuum moulding. The shrinkage allowance was not measured, but would be of interest in future research. Sharp edges might form some problems, as chip breakage was observed in the corners of the 4 mm thick sample.

Figure 37 The cross section of the 4 mm thick vacuum moulded sample. The thickness varied from 3,2 mm to 3,9 mm along the arch. In the spot pointed with a circle the thickness was over 4 mm, because the sample was pressed through the silicon film locally during the vacuum moulding.

Figure 38 Cross sections of the 2 mm thick vacuum moulded samples. The thickness varied from 1,6 mm to 2,0 mm on the straight part of the shape (facing down in the figure). The thickness of the corners of the moulded sample varied from 1,0 mm to 1,8 mm.

The samples were sawn in half for thickness measurements. The thickness of the cross section of the 4 mm thick vacuum moulded samples varied from 3,2 mm to 3,9 mm along the arch. Near the end of the arch the thickness was over 4 mm, because the sample was pressed through the silicon film locally during the vacuum moulding (Figure 37). The thickness of the cross section of the 2 mm thick vacuum moulded samples varied from 1,6 mm to 2,0 mm on the straight part of the shape. The thickness of the corners of the moulded sample varied from 1,0 mm to 1,8 mm (Figure 38).

5 Results and Discussion: Qualitative Analysis

Different ideas and possibilities for the material were gathered in multiple ways to get a wide ideation range. The base for ideation was drawn from literature and the existing knowledge of the material. To get inspiration and innovative ideas two visits were made: one to product development unit of ISKU Oy and one to the industrial design department of Aalto University School of Arts, Design and Architecture (Aalto ARTS). The vacuum moulding experiment was conducted during the visit to Aalto ARTS (9.2.2015). The hands-on experience of the material was tested in two workshops, where the participants were students of Aalto University.

5.1 Concept Screening

The research for possible novel applications resulted in a wide set of suggestions, some impossible from the start. However, many potential concepts arose and they were taken to closer investigation. The first screening of the potential concepts is presented in Table 7, where the positive (pros) and negative (cons) features of the concepts are put together. The features give the concept a final score, which determines whether the development of the concept is continued or not. Scores below zero lead to rejection.

Ideation for the material during the visit at Aalto ARTS was done along with the vacuum moulding experiment. As the material replicated the moulds excellently, lots of ideas emerged inter alia combining with other wood based materials, adding the material to a material library e.g. in the California College of the Arts and using the material with customized biodegrading. Especially the way and rate of biodegrading and possibilities for upcycling were of interest.

The hands-on work at the workshops gave tangible experiences of the possibilities of the material. The general impression was that even people totally new to the material can use it rather easily and form it according to their plans. The participants were highly productive in the brainstorming phase of the workshop, which also brought out questions about temperature behaviour, time and conditions for biodegradability, strength and toughness. Non-toxicity and biodegradability were seen as value adding features.

The visit to product development unit of ISKU Oy was mainly to figure out the potential for Woodcast® in furniture industry. The development team found the material highly interesting both for modelling and manufacturing furniture. At the moment ISKU Oy uses formable plywood UPM Grada (see Section 2.4.1), which needs to be heated up to 95 °C for moulding and Woodcast® was seen as a potential competitor or a material to combine with UPM Grada. Characteristics such as abrasion and surface cleaning durability, fire safety and UV-resistance came up in the discussion about the materials suitability for furniture.

Modelling achieved the highest score in the concept screening (Table 7). The possibility to easy 3D moulding was seen as highly attractive solution for modelling needs. Other praised characteristics were non-toxicity, reusability and the low working temperature, which play a significant role in such hands-on activity as modelling. The major issue with modelling is that the material needs a separate heating device. In scenography and staging the needs for the material are similar to modelling, but the product dimensions are larger. The price becomes also an issue in scenography and staging if the material consumption rises e.g. in major play props.

Packaging seemed to be a potential application due to the material's 3D mouldability and compatibility with other materials. Compared to other packaging solutions, such as plastics or cardboard, the strength and durability of Woodcast® are competitive. In small batches the cost of Woodcast® is too high for common packaging uses, which mainly compete with price by bulk production.

Use of Woodcast in acoustic applications such as loudspeaker enclosure or acoustic element for indoor use was discussed especially during the visit at Aalto ARTS. The features supporting applications in acoustics were 3D mouldability, compatibility with other materials and possibility to get Woodcast® in different colours by dying the plastic and/or wood parts. The major drawback for acoustic applications from Woodcast® is the low melting temperature, as the temperature requirements for interiors and furniture are higher.

Quite close to the current casting use, the idea of a first aid kit material came up. Woodcast® could serve as a multipurpose material for fieldwork, due to its light weight, reusability and non-toxicity. The challenge for using would be the heating up of the material, because it catches fire rather easily. Boiling water is also out of question, as the material absorbs large amounts of moisture in temperatures above 65°C.

Furniture and interior applications of Woodcast® were mainly envisaged by the product development team of ISKU Oy. The lightness, pleasant feel and possibility to combine Woodcast® with other materials were found as potential exploitable characteristics. Customizing and details, especially done with 3D moulding, for furniture and interiors were considered as promising uses. The main drawback is again the low melting temperature, but also the scent of the material was found disturbing.

One opportunity for the material was seen in landscaping. During the visit at Aalto ARTS functional landscaping i.e. controlled biodegradability, combined support and fertilisation and water absorption properties came up in the discussion. At the moment all of these properties of Woodcast® are not investigated, but in theory controlled biodegradability and combined support and fertilization are possible to put into practise. The water absorption properties measured from Woodcast® do not strongly support this kind of application as the behaviour of the material changes with temperature.

3D-printing with the material came up several times during the research. Low working temperature was seen as a possibility, but the size of the wood chips ruled out most of the printers, as they need more homogenous material for manufacturing. It might be possible to use Woodcast® in industrial size 3D-printers, but this was not studied further. Other aspects like biodegradability and price did not bring any notable advantage compared to other materials.

Table 7 Screening of the potential concepts according to concept screening matrix model (Table 3). + = advantage, ++ = major advantage, - = drawback, -- = major drawback. Scores below zero are ruled out. * = The possibility of large-panel printing came out so late in the process, that there was no time for further investigation. (Continued on the next page)

Concept screening matrix				
Concept	**Pros**	**Cons**	**Score**	**Continue?**
3D printing	low working temperature +	particle size too large --	-1	NO
Acoustics	3D mouldability ++ combining with other materials possible +	low melting temperature -	2	YES
First Aid kit	easy to transport + multiple uses + reusable +	heating needed -	2	YES
Furniture	lightness + pleasant feel + combining with other materials +	low melting temperature -- scent of the material -	0	YES
Interiors	3D mouldability ++ combining with other materials possible + customizing and details + Wood's effect on indoor climate and human well-being +	low melting temperature -- scent of the material -	1	YES
Large-panel printing*	3D mouldability ++ digital printing possible +	production dimensions - behaviour of print with moulding?	-	NO
Landscaping	controlled biodegradability + combined fertilization and support +	production dimensions - water absorption properties -	0	YES
Modelling	non-toxic + easy to mould + re-usable + 3D mouldability ++	heating device needed -	4	YES

Table 7 Screening of the potential concepts according to concept screening matrix model (Table 3). + = advantage, ++ = major advantage, - = drawback, -- = major drawback. Scores below zero are ruled out. (Continued from the previous page)

	Concept screening matrix			
Concept	**Pros**	**Cons**	**Score**	**Continue?**
Packaging	3D mouldability ++ combining with other materials possible +	price -	2	YES
Sports protection and equipment	customization +	low melting temperature --	-1	NO
Scenography and staging	non-toxic + easy to mould + re-usable + 3D mouldability ++	production dimensions - price -	3	YES
Temporary constructions	3D mouldability + combining with other materials possible +	strength - low melting temperature - price -	-1	NO

One of the very first suggestions for the use of the material was sports protection and equipment. The material would enable high degree of customization for example in shin pads or wrist guards. The low melting temperature becomes an obstacle also in this application as the material does not maintain its shape if it gets heated.

Temporary constructions fall into the same category as furniture. 3D mouldability and combining with other materials are advantages, but they are overrun by the drawbacks with current strength properties, low melting temperature and price. Large-panel printing links to temporary constructions, because often e.g. fair stands have a print on them according to company’s wishes. The questions about digital printing possibility, production dimensions and behaviour of print when moulded could not be researched enough in the timeframe of this thesis.

In each part of a product development process it is essential to analyze also the work itself by paying attention, if it is possible, in combining and improving the concepts under examination. In this case the concepts related to acoustics, furniture and interiors were combined to one as they were noticed to require similar properties from the material. Modelling and scenography and staging were also combined, as they fundamentally mean the same in different dimensions. These combinations are treated as two concepts in Section 4.2.

5.2 Concept Evaluation

The concepts screened for deeper analysis in Section 4.1 are presented in Table 8. The screening is done from four viewpoints, which are weighed according to their importance at this point of the development process. The viewpoints and weightings are formed according to the methods of Ulrich & Eppinger (2000). The criteria for scoring are

- Material and manufacturing
  - The material can be used in the application straight from the mill as it is. If the structure, melting point, density etc. must be altered to meet the needs of the application, the score is lower. The amount and dimensions of the material are restricted in the mill at the moment. If there's a need for large or thick panels, the ease of manufacturing score gets lower.
- Return of investment
  - The amount of investments which are needed in the development stage of the concept e.g. for manufacturing, marketing and testing and how fast the investment will pay itself back. The price of Woodcast® is approximately 5 €/kg.
- Competition
  - The available markets are observed on European level. Amount of competitors and the type of the market (bulk/niche) affect this score.
- Time to market
  - The time and effort needed to get the product to the customer. High score stands for short time to market.

Table 8 Scoring of the potential concepts according to the concept scoring matrix model (Table 4). Criteria are evaluated with a scale of 1-5, where 1 is the worst and 5 is the best value. * = Acoustics, Furniture and Interiors

	Concept scoring matrix					
	AFI*	**First Aid**	**Landscaping**	**Modelling**	**Packaging**	**Weight**
Material and manufacturing	2	2	4	5	5	**15 %**
Return of investment	3	4	2	5	4	**50 %**
Competition	4	2	2	1	3	**25 %**
Time to market	1	5	2	4	4	**10 %**
Total score	2,5	3,25	2,5	3,75	4	**100 %**
Weighed score	2,9	3,3	2,3	**3,9**	**3,9**	

In the light of material properties and production possibilities landscaping, modelling and packaging reached the highest scores (Table 8). For all of these the low working temperature was an advantage as well as the current production dimensions were suitable for prototyping and implementations. In vacuum moulding tests (see Section 4.3, p. 46) the material was discovered to replicate different moulds excellently, which is important in modelling operations. The possibility to reuse the material when the model is not needed anymore was also seen as a positive feature at Aalto ARTS and ISKU Oy. Thicker or wider plates or other shapes for the models might be wanted, but they are not currently available.

In landscaping larger dimensions and new material mixes would probably be needed to bring value addition for the product. For prototyping e.g. honeycomb structures the current manufacturing dimensions are good enough (Hansen 2008). When considering packaging, the vacuum moulding results support the concept, but for better market entering potential, properties such as water or puncture resistance, should be examined further.

Acoustics, furniture and interiors (AFI) and first aid material –concepts gained only two out of five points from the viewpoint of material properties and production possibilities. In the case of AFI, furniture standards set the temperature limits, which rule out Woodcast® because of too low melting point. Although the melting point could be altered, the industry would need large dimension panels (European Bioplastics e.V. P. 2013b), which are not available at the moment. As the material is already used for casting, first aid material sounded like a potential application. Using Woodcast® as a first aid material would otherwise be easy, but there are challenges to heat up the material in field conditions, as it easily catches fire. Boiling could be an alternative option, but it would require better water resistance from the material.

The best return of investment (ROI) could come from modelling, as it can be marketed and sold with current product portfolio. Investment costs would mostly connect to branding and marketing of the product. ROI of packaging and first aid concepts is more or less on the same level. In first aid use the development stage would mainly need “hands-on” testing as it is already used for casting. In packaging use the characteristics are suitable for direct prototyping. With both concepts it is possible to do testing with small batches. The profitability rises as the batch size increases, which could happen e.g. if some company takes the material in their product portfolio.

The concepts of AFI and landscaping do not perform in ROI as well as the previously mentioned concepts. For AFI the main issue is that the melting point of the material needs to be altered, which consumes time and resources especially in the testing phase. On the other hand, the furniture industry is trying new materials, so there is a chance to start with small volume (European Bioplastics e.V. P. 2013b). In landscaping the price comes along, because the amounts needed are large and price competition plays a notable role (Hansen 2008). If there’s no co-operating company, the testing requires lots of instruments and takes a lot of time because of biodegradability testing.

Considering the markets and competition AFI got the highest score. The market for home related products is big in Europe and there are not too many easily mouldable ecological products available, which could be used for acoustics, furniture or interiors. Green values are getting lots of publicity in furniture industry e.g. in form of wood origin certificates like FSC and PEFC. For example ISKU Oy has a unique own line for UPM Grada, which could be used in principle also for moulding Woodcast®.

Packaging got 3 out of 5 points in the category of competition. The ecological nature and recyclability of the material were the most competitive attributes, along with potential remoulding and reusing possibility. The challenges for packaging use are high competition and bulk production, where the price of Woodcast® is far from competitive. If the reuse, rather than recycling, of the material would be possible, it would improve the competitiveness as the product life cycle would be extended. There could also be prospects in special packaging products such as luxury items.

First aid, landscaping and modelling performed rather poorly in the viewpoint of competition. For first aid and modelling the markets are niches, where other functional materials are competing with the market shares. If the first aid concept would be accepted as a multiuse and lightweight material, it might be able to enter the markets of camping and extreme hiking, which have larger volumes in sales. For modelling use there is lots of competition and the material does not directly substitute any existing modelling material. On the other hand modelling could cover both expert (e.g. designers, architects) and consumer markets as the material is suitable to handle even for kids due to its non-toxicity. Entering the expert market might be easier, but the profit is higher in consumer markets. In the case of landscaping the main drawback compared to competitors is the price. It is also questionable, that is there market potential for a functional (water holding, controlled biodegradability, combined fertilization etc.) landscaping material.

The fastest time to market would be with first aid use, as the material is ready for marketing as a new brand. In addition, the present use as casting material could be used as a reference for first aid applications. When considering modelling, the material is as well ready for marketing as a new brand, but there would be a need for wider branding and targeted marketing for potential first adopters of the product. For packaging use the prototyping and introduction of the concept would be relatively easy, but it might come to way that from the side of the packaging manufacturers there are neither the equipment for industrial manufacturing nor the ability to process the material.

With the concepts of AFI and landscaping the time to market would be notably longer compared to the other concepts under investigation. The demonstration of both applications is possible already with the existing material, but the features of the material do not meet all the requirements yet. Time consuming measures like alteration of the melting point and defining of the biodegradability rate, would hold off the product release. The product could not be marketed and sold in advance, because the properties are not yet verified. Moreover, there might be some certificates to apply for the products to be competitive on the market.

The result of the concept scoring was that modelling and packaging were the most potential concepts (Table 8, p. 53). The weights for the four viewpoints were generated according to the impression of the company. The return of investment was seen as the most important attribute at this point of the research for conceptualization. Modelling and packaging were equal in the weighed scoring, but the average of packaging was higher, so it was chosen to further investigation.

5.3 The Most Potential Application: Packaging

According to Duhovic et al. (2008) package is for protection, transportation, preservation and display. The main points of packaging are to protect the item from physical and chemical damage, provide convenience during handling and tempt the customers to buy the product. Packaging is also divided to three categories:

- primary packaging, where the packaging material is in direct contact with the product,
- secondary packaging, where the packaging material protects the product and
- tertiary packaging, where the packaging material protects the product from mechanical damage during handling and transportation.

In packaging Woodcast® would fall into the primary and secondary categories. Low melting temperature and high price (~5 €/kg) mostly rule out the tertiary packaging. In secondary and tertiary packaging cardboard and wood products are hard competitors for natural-fibre –biopolymer composites, as they are available in large variety and a relatively low price. To be competitive against conventional products, the biocomposite materials need to bring additional value to the package, while keeping the density low. This can be in many cases achieved by tailoring the mechanical and chemical properties of biocomposites to meet the requirements of the packaging. For example, to be able to use the label "compostable", 90% of the material needs to be broken down in 6 months in compost. (Duhovic et al. 2008)

New bio-based solutions are searched for packaging because of the demand for environmentally friendly products from regulations and consumers. Approximately 40% of the plastics consumption in the world is used in packaging sector. The recycling of plastics is difficult because the large variety of them. Natural fibres combined with biodegradable polymers are one solution to this issue. Although the polymers are expensive, the use of natural fibre reinforcement reduces the amount of polymer needed and so also the price. In addition, natural fibres bring additional stiffness, strength and lightness to the composite structure. (Duhovic et al. 2008) Woodcast® would answer to this kind of demand and it would also be competitive against other solutions with e.g. in use with groceries (see section 2.5.3 p. 28), X-ray permeability and the self-adhesive nature of it.

Woodcast® is theoretically suitable for injection moulding, extrusion, thermoforming and blow moulding and vacuum moulding, which are all techniques used in packaging industry. Initial testing for vacuum moulding was done for this thesis, where Woodcast® performed really well (see Section 4.3). Structurally Woodcast® is already suitable for packaging, but its degradability, barrier and absorption properties and non-structural functionalities (e.g. abrasion resistance) are not known to sufficient extent to analyze its total potential in packaging. A general comparison of biocomposites against other packaging materials is illustrated in Figure 39.

Packaging material property	*Excellent*						*Poor*
Structural properties	Metals (aluminium, steel)	**Bioplastics/ biocomposites**	Plastics	Glass	Wood	Paper/board Moulded pulp	Textile
Manufacturability	Plastics	**Bioplastics/ biocomposites**	Paper/board Moulded pulp	Metals (aluminium, steel)	Glass	Textile	Wood
Barrier properties	Metals (aluminium, steel)	Glass	Plastics	**Bioplastics/ biocomposites**	Wood	Paper/board Moulded pulp	Textile
Environmentally friendly	**Bioplastics/ biocomposites**	Paper/board Moulded pulp	Wood	Metals (aluminium, steel)	Textile	Plastics	Glass
Non-structural functionality	Paper/board Moulded pulp	Plastics	**Bioplastics/ biocomposites**	Metals (aluminium, steel)	Wood	Glass	Textile
Light weight	Paper/board Moulded pulp	**Bioplastics/ biocomposites**	Textile	Plastics	Wood	Metals (aluminium, steel)	Glass

Figure 39 Comparison of packaging materials (Duhovic et al. 2008).

The latest trends and innovations of packaging sector were mapped at EMPACK – fair 7.-9.10.2015 at Messukeskus, Helsinki. EMPACK is a trade fair, open only to representatives from the business and public sectors. (EMPACK, 2015) One of the largest topics at the fair was intelligent packaging concepts, which involve the customer in some way by the package. This could be achieved e.g. by creating trends relating to the appearance and material of the package or by letting the customers choose the packaging material for a certain product themselves. Other themes were barrier plastics, the variety of eco-labels, excessive packaging at Asia etc. Although the variety of themes was broad, ecological awareness and packaging as a tool for interaction came along in several occasions.

The markets for biocomposites in general are broadening as the demand for advanced technical properties and functionality is increasing and at the same time there is more and more suitable production facilities founded. Accompanied with the trend of sustainable products and new recycling options, the future of the biocomposites looks promising. (Duhovic et al. 2008)

5.4 Further Development for Packaging

The concept of packaging use of Woodcast® needs further development first in market research and positioning. This material is a product in search for a market, so it needs to be considered that which sector of packaging would be suitable for entering the market. The most competitive properties of the material, such as biodegradability, are strongly linked to green values.

There is a general market pull for sustainable engineered solutions. According to Baillie (2004) there is also a demand for low temperature and pressure processes, such as vacuum moulding, for composites in the packaging industry. To measure customer response, it could be beneficial to organize different workshops for industry representatives. One possibility for market research and concept design could be co-operation with e.g. Aalto University, where the company could participate in an interdisciplinary business collaboration course.

Secondly, deeper knowledge of the material properties should be acquired to gain better market entering potential. For example water and puncture resistance are characteristics of which there is very little information. In addition to technical testing, so called “material in use” observations through further prototypes would be useful. Especially the vacuum moulding experiment should be repeated in these “material in use” –tests because, as said before, the packaging industry uses the technique widely (Duhovic et al. 2008).

6 Conclusions and Recommendations

Woodcast® was found to be flexible and protean material suitable for multiple development paths. During the research the knowledge of many properties was deepened, but at least as many new questions about the behaviour and characteristics arose. The objectives of the thesis were:

- to position the material by benchmarking,
- to map new application possibilities for the material,
- to screen out one idea of the new application possibilities and
- to suggest further development model for the chosen idea.

As the material has potential to so many directions, the framing of the topic to investigate more closely took a lot of time. In addition, the initial focus was changing throughout the research from consumer targeted applications to industrial scale products.

The benchmarking of Woodcast® was committed by comparing it to other WBCs. In addition to the known properties, the tensile strength and water absorption tests made it possible to compare the material in more detail with other composite materials. The main observations were that the bending strength and thickness swell in room temperature are competitive in the light of this comparison, especially against MDF and particleboard (see Section 2.6, p. 29).

The most important findings considering the material properties of Woodcast® were its characteristics in 3D moulding and its water absorption tendency. The material was able to absorb almost worth its own weight of moisture in temperature above the plastic melting temperature of 65 °C (see Table 6, p. 36). The vacuum moulding experiment showed that there would be potential to use Woodcast® in applications needing excellent replication of moulds. The pleasant haptic properties of the material should not be underestimated in this connection, as many consumer items are manufactured by different moulding procedures.

The screening and scoring of the gathered applications pointed out the strengths and weaknesses of Woodcast®, which varied from application to application. The method was effective and fast, but gave only a vast insight to the applications which were screened out. On the other hand, the progress is documented and so the abandoned ideas can be investigated later if necessary.

Considering the material in general, the recommendation for further actions is to examine the behaviour and properties more thoroughly. The data from tensile strength, water absorbance and vacuum moulding acquired in this research can be considered as preliminary observations for wider studies according to the interests of the company. Other properties to take into consideration are biodegradability and the effect of rapid temperature alterations on Woodcast®.

Linking to the previously mentioned properties comes the life cycle of the material when stored. As the material is often stored in the heater, the effect of time, temperature and number of re-heating cycles are of interest. In addition, the degradation of the wood particles in high temperatures should be investigated, as it will most probably affect the strength properties of the product. The result of this research would be the knowledge of how long the product can be stored in the heater and how many heating cycles it endures.

If the packaging use of the material is investigated further, the first steps should be prototyping and measuring customer response, preferably these two combined. Material testing and improvement could be then done in tandem with the product iteration. A very good coordination and cooperation between R&D, marketing and other departments of the company would be crucial to get the best benefit from this process.

References

Abdul Khalil, H.P.S.; Bhat, A.H.; Ireana Yusra, A.F. (2012) *Green composites from sustainable cellulose nanofibrils: A review.* Carbohydrate Polymers. Vol. 87:2, pp. 963-979.

Akovali, G. (ed.) (2001) *Handbook of Composite Fabrication*. Smithers Rapra, Shrewsbury, GBR. 198 p.

Alpha Particle Board Pvt. Ltd. (2015) *Waterproof Particle Board.* (Cited 28.8.2015) Available at: http://www.alphaparticleboard.com/waterproof-particle-board-2373121.html

Anttila, A. (2011) *Puuhakkeesta kipsiä - suomalaiskeksintöä viedään sairaaloihin ulkomaille.* Kauppalehti (magazine). Published 27.5.2011. (Cited 9.12.2014) Available at: http://www.kauppalehti.fi/omayritys/puuhakkeesta+kipsia+-+suomalaiskeksintoa+viedaan+sairaaloihin+ulkomaille/20110576785

ASM International Handbook Committee. (1987) *Engineered materials handbook: 1 Composites*. Metals Park, OH. 983 p.

Auvinen, S.; Isomäki, O.; Koponen, H.; Saimovaara, J.; Tiainen, Juha; Tiainen, Jouko; Tolvanen, P. (2002) *Puusepänteollisuus. Puutuoteteollisuus 3.* Edita, Helsinki. 266 p.

Averous, L.; Boquillon, N. (2004) *Biocomposites based on starch: thermal and mechanical behaviours.* Carbohydrate polymers, Vol. 56:2. pp. 111-122.

Baillie, C. (ed.) (2004). *Green Composites - Polymer Composites and the Environment*. Woodhead Publishing, Cambridge. 320 p.

Bulota, M. (2012) *Deformation and fracture mechanisms in nanocellulose reinforced composites.* Aalto University, Department of Forest Products Technology. Aalto University publication series, doctoral dissertations 109/2012. 65 p.

Chen, W.; Atsuta, T. (2008). *Theory of Beam Columns, Volume 1 - In-Plane Behavior and Design.* J. Ross Publishing, Inc. 528 p.

Dinwoodie, J. M. (2000) *Timber: Its Nature and Behaviour.* Taylor & Francis, New York. 272 p.

Duhovic, M.; Peterson, S.; Jayaraman, K. (2008) *Natural-fibre –biodegradable polymer composites for packaging.* Properties and Performance of Natural-Fibre Composites. CRC Press, Boca Raton, Boston, New York, Washington DC. pp. 301-329.

EMPACK –fair 7.-9.10.2015, Messukeskus, Helsinki. Available at: http://www.easyfairs.com/events_216/empack-2015_67307/empack-2015_67308/

Eichhorn, S.J.; Dufresne, A.; Aranguren, M.; Marcovich, N.E.; Capadona, J.R.; Rowan, S.J.; Weder, C.; Thielemans, W.; Roman, M.; Renneckar, S.; Gindl, W.;Veigel, S.; Keckes, J.; Yano, H.; Abe, K.; Nogi, M.; Nakagaito, A.N.; Mangalam,A.; Simonsen, J.; Benight, A.S. (2010) *Review: current international research into cellulose nanofibres and nanocomposites*. Journal of Materials Science. Vol.45:1, pp. 1-33.

Eichhorn, S. J.; Young, R. J. (2003) *Deformation micromechanics of natural cellulose fibre networks and composites.* Composites Sci. Technology. Vol. 63, pp. 1225-1230.

Encyclopædia Britannica Online. (Cited 13.1.2015). Available at: http://academic.eb.com.libproxy.aalto.fi/

EPS Poland (2015) *Phenolharzbeschichtetes Sperrholz Premium.* (Cited 28.8.2015) Available at: http://www.epspoland.de/premium.php?sperrholz=foliert-premium

Erpa Orman (2015) *Profiles.* (Cited 28.8.2015) Available at: http://www.erpaorman.com.tr/images/menu-box/profil.jpg

European Bioplastics e.V. P. (2013a) *Bioplastics, facts and figures.* European Bioplastics: Institute for Bioplastics and Biocomposites, Berlin. (Cited 7.5.2015) Available at: http://www.muoviteollisuus.fi/fin/muovitieto/julkaisukirjasto/muut_julkaisut/

European Bioplastics e.V. P. (2013b) *European Bioplastics: Driving the Evolution of Plastics.* European Bioplastics: Institute for Bioplastics and Biocomposites, Berlin. (Cited 7.5.2015) Available at: http://www.muoviteollisuus.fi/fin/muovitieto/julkaisukirjasto/muut_julkaisut/

European Panels Federation EPF (2014) *About the European Panel Federation.* (Cited 28.8.2015) Available at: http://www.europanels.org/

European Parliament. (2000) *Directive 2000/53/EC of the European Parliament and of the Council of 18 September 2000 on End-of-Life Vehicles*. Official Journal of the European Communities. 15 p.

Europäischer Wirtschaftsdienst GmbH EUWID. (2012) *Wood Products and Panels*. (Cited 28.8.2015) Available at: www.euwid-wood-products.com

EWPAA Engineered Wood Products Association of Australasia. (2008) *Facts About Particleboard and MDF.* (Cited 11.10.2015) Australian Wood Panels Association Incorporated, PO Box 158, Coolangatta Qld 4225. 41 p. Available: http://www.ewp.asn.au/library/downloads/ewpaa_facts_about_pb_and_mdf.pdf

Fagerstedt, K.; Pellinen, K.; Saranpää, P.; Timonen, T. (2005) *Mikä puu - mistä puusta.* Yliopistopaino. Helsinki. 184 p.

Faostat -Food and Agriculture Organization of the United Nations, statistics division. (2013) *Forestry statistics.* (Cited 20.5.2015) Available at: http://faostat3.fao.org/browse/F/*/E

Fathollahzadeh, A.; Enayati, A.; Erdil, Y. (2013) *Effect of laboratory-accelerated aging treatment on the ultimate strength of a 4-sided MDF kitchen cabinet.* Turkish Journal of Agriculture & Forestry. Vol. 37:5, pp. 649-656.

Feldman, D. (1989) *Polymeric Building Materials*. Elsevier Applied Science. London. 575 p.

Flaxwood. (2011) *Flaxwood. Fine Electric Guitars.* Official website. (Cited 1.10.2015) Available at: http://www.flaxwood.com/home/

Gordon, J.E. (2006) *The New Science of Strong Materials or why you don't fall through the floor*. Princeton University Press. Princeton and Oxford. 287 p.

Green Dot Holdings LLC (2013) *Product Description Terratek® BD 4015*. Technical data sheet. (Cited 15.10.2015) Available at: http://www.greendotpure.com/images/pdf/GD_BD_4015.pdf

Greenwood SRL (2011) *Technical datasheet Greenwood Deck.* (Cited 14.10.2015) Available at: www.greenwood-venice.com/filemanager/689.pdf

Hansen, E. (2008) *Market and innovation considerations in development of natural/wood-fiber composites.* Properties and Performance of Natural Fibre Composites. CRC Press, Boca Raton, Boston, New York, Washington DC. pp. 356-372.

Helsingin kaupunki. (2015). *Central library 2017 official webpage: Käännös on moniulotteinen talo.* (Cited 8.5.2015) Available at: http://keskustakirjasto.fi/voittaja/

Hill, C.; Hughes, M. (2010). *Natural Fibre Reinforced Composites: Opportunities and Challenges.* Journal of Biobased Materials and Bioenergy. Vol.4:2, pp. 148–158.

Holbery, J.; Houston, D. (2006). *Natural-fiber-reinforced polymer composites in automotive applications*. The Journal of The Minerals, Metals & Materials Society. Vol. 58:11, pp. 80-86.

Hollaway, L. (1993) *Polymer Composites for Civil and Structural Engineering*. Chapman and Hall Inc. Glasgow. 259 p.

Huda, M.S.; Drzal, L.T.; Ray, D.; Mohanty, A.K.; Mishra, M. (2008) *Natural-fiber composites in the automotive sector*. Properties and Performance of Natural-Fibre Composites.CRC Press, Boca Raton, Boston, New York, Washington DC. pp. 221-268.

Jung, Y.H.; Chang, T.; Zhang, H.; Yao, C.; Zheng, Q.; Yang V.W.; Mi, H.; Kim, M.; Cho, S. J.; Park, D.; Jiang, H.; Lee, J.; Qiu, Y.; Zhou, W.; Cai, Z.; Gong, S.; Ma, Z. (2015) *High-performance green flexible electronics based on biodegradable cellulose nanofibril paper.* Nature Communications. Vol 6:7170. pp. 1-11.

Kairi, M. (2005) *Interaction of R&D and business development in the wood products industry, case Kerto®– Laminated Veneer Lumber (LVL).* Report 95, Helsinki University of Technology, Department of Forest Products Technology, Laboratory of Wood Technology. Pikaset Oy, Helsinki. 225+15 p.

Koponen, H. (2002) *Puutuoteteollisuus 4: Puulevytuotanto*. Edita Oy, Helsinki. 201p.

Kulttuuritehdas Korjaamo. (2015) *Allas – Helsinki Pool. Korjaamo official website.* (Cited 8.5.2015) Available at: http://www.korjaamo.fi/en/allas

Lammhults Möbel AB. (2015) *Imprint chair*. Official website (Cited 1.10.2015) Available at: www.lammhults.se

Leiniö, V. (2014) *Woodcast® natural aging report*. Muovipoli Oy. Published 5.6.2014. (Cited 5.5.2015) Available at: www.**woodcast**.fi/fi/koulutusjamateriaalit/artikkelitjajulkaisut

Leinonen, T. (2014) *Muotoilukasvatus. MUTKU - muotoilukasvatusta peruskouluun -opetuskokonaisuuden opetussuunnitelman laatimiminen.* Aalto University School of Arts, Department of Design. Master's Thesis. 108 p.

Lindfors, N.C.; Salo, J. (2012). *A Novel Nontoxic Wood-Plastic Composite Cast.* The Open Medical Devices Journal. Vol. 4:1-5. 5 p.

Lou,S.Y.; Chou, T.W. (1992) *Composite Applications – The Role of Matrix, Fibre and Interface.* Editors: Vigo, T.L.; Kinzig B.J. VCH Publishers Incorporated, New York, USA. 407 p.

McCallum, D. (1996) *The Manufacturing Process Medium Density Fibreboard.* Australian National University, Faculty of Forest Products Technology. (Cited 24.7.2015) Available at: http://fennerschool-associated.anu.edu.au/fpt/mdf/manufacture.html

Merivuori, K.; Koskinen, A. (2009) *Puutuotemarkkinoiden kehitysnäkymät*. Report for Finnish Ministry of Employment and the Economy. Pöyry Forest Industry Consulting Oy. 52 p.

Metsäteollisuus ry. (2001) *Vanerikäsikirja.* Kirjapaino Markprint Oy, Lahti. 65 p.

Metsä Wood. (2012) *KERTO® kantaviin rakenteisiin.* (Cited 24.6.2015) PDF-file, available at: http://www.metsawood.com/fi/tuotteet/kerto/Pages/Kerto-S.aspx

Meyers, M.A.; Chen, P.; Lin, A.Y.; Seki, Y. (2008) *Biological Materials: Structure and mechanical properties*. Progress in Materials Science. Vol. 53:1, pp. 1-206.

Mootee, I. (2013) *Design Thinking for Strategic Innovation: What They Can't Teach You at Business or Design School*. John Wiley & Sons, Somerset, NJ, USA. 210 p.

Muovipoli Oy. (2011) *Onbone Oy, raportti, OMNICAST- muovikomponentin vaikutus taivutuslujuuteen.* Muovipoli Oy, Nastola. 5 p.

Newman, R.H.; Staiger, M. P. (2008) *Cellulose nanocomposites.* Properties and Performance of Natural-Fibre Composites. CRC Press, Boca Raton, Boston, New York, Washington DC. pp. 209-217.

Onbone Oy. (2014). *Woodcast® official website*. (Cited 9.12.2014) Available at: http://www.woodcast.fi/en

Onemed Oy. (2014) *Tervetuloa nopeus ja helppous!.*OneMed official homepage. (Referred 5.5.2015) Available at: http://www.onemed.fi/Templates/Template.aspx?id=9814870

Oxford English Dictionary. (Cited 13.1.2015). Available at: http://www.oed.com.libproxy.aalto.fi

Pat. WO 2010/103186 A2. *Novel materials*. Antti Pärssinen, Finland. App. PCT/FI2010/050185, 11.03.2009. Publ. 16.09.2010. 30+4 p.

Pirhonen, E.; Pärssinen, A.; Pelto, M. (2013). *Comparative study on stiffness properties of WOODCAST® and conventional casting materials.* Prosthetics and orthotics international. Vol. 37:4. pp. 336-339. 5 p.

Plasthill Oy. (2015) *Kupilka.* Official website. (Cited 1.10.2015) Available at: http://kupilka.fi/

Réh, R. (2013). *Admixtures of non-wood lignocellulosic materials in combination with wood particles in composite materials.* ProLigno. Vol. 9:4, pp. 519-524. 6 p.

Schäffer, T. E.; Ionescu-Zanetti, C.; Proksch, R.; Fritz, M.; Walters, D. A.; Almqvist, N.; Zaremba, C. M.; Belcher, A. M.; Smith, B. L.; Stucky, G. D.; Morse, D. E.; Hansma, P. K. (1997) *Does Abalone Nacre Form by Heteroepitaxial Nucleation or by Growth through Mineral Bridges?* Chemistry of Materials. Vol. 9:8, pp. 1731–1740.

SRV; Stora Enso Building and Living. (2015) *Wood City official homepage.* (Cited 8.5.2015) Available at: http://www.woodcity.fi/en/

Sreekumar, P. A.; Thomas, S. (2008) *Matrices for natural-fibre reinforced composites.* Properties and Performance of Natural-Fibre Composites. National Institute of Technology Calicut and Mahatma Gandhi University, India. pp. 67-126.

Ritschkoff, A.; Koskinen, J.; Paajanen, M. (eds.) Organized by VTT Technical Research Centre of Finland. (2006) *Applied Material Research at VTT.* Edita Prima Oy, Helsinki. 338 p.

STT (Finnish News Agency). (2012) *Tiedote/Kemianteollisuus ry: Kemianteollisuuden innovaatiopalkinto 2012: Puukomposiitti mullistaa kipsaamisen.* Kauppalehti (magazine) webpage. (Cited 9.12.2014) Available at: http://www.kauppalehti.fi/5/i/yritykset/lehdisto/stt-info/tiedote.jsp?direct=true&selected=kaikki&oid=20120401/13351864245640

Suomen Metsäyhdistys Ry. (2012) *Metsäpäivät 2012: Huomionosoitusten perusteet.* Official announcement. (Cited 9.12.2014) Available at: http://www.smy.fi/smy/HRdeve.nsf/51d18aa803f85756c225704d003ba42c/7dc98ebabfe42653c2257ab0003b71c6?OpenDocument

Taha, M.A.; El-Sabbagh, A.M.; Taha, I.M. (eds). (2010).*Key Engineering Materials, Volume 425: Trends in Composite Materials and their Design.* Trans Tech Publications, Durnten, Zurich, CHE. 285 p.

Tomsic, J. L. (2000) *Dictionary of Materials and Testing (2nd Edition) - critical fiber length.* Society of Automotive Engineers, Inc. (Cited 24.2.2015) Available at: http://app.knovel.com/hotlink/pdf/id:kt00861J33/dictionary-materials/critical-fiber-length

Ulrich, K. T.; Eppinger, S.D. (2000) *Product Design and Development.* The McGraw-Hill Companies Inc. 358 p.

UPM Grada. (2015). *Product info – Innovative material for furniture design & Interior architecture*. Official website. (Cited 20.5.2015) Available at: http://www.upmgrada.com/#products

UPM-Kymmene Oyj. (2014) *UPM and Metropolia proudly present: the Biofore Concept Car drives sustainable change through innovative use of biomaterials.* Official website. (Cited 1.10.2015) Available at: https://www.upm.com/en/media/all-news/pages/upm-and-metropolia-proudly-present-the-biofore-concept-car-drives-sustainable-ch-001-tue-04-mar-2014-09-31.aspx

UPM-Kymmene Oyj. (2015a) *About plywood.* (Cited 18.5.2015) Available at: http://www.wisaplywood.com/Products/about-plywood/Pages/Default.aspx

UPM-Kymmene Oyj. (2015b) *UPM ProFi– Design meets performance.* (Cited 2.9.2015) Available at: http://www.upmprofi.com/Pages/default.aspx

Uusi Puu –hanke. (2014) *Uusi Puu 2014 –kilpailu.* (Cited 9.2.2015) Available at: http://www.uusipuu.fi/kilpailu

Vinylplus. (2014) *PVC Recycling Technologies*. Vinylplus, EU. (Cited 7.5.2015) Available at: http://www.muoviteollisuus.fi/fin/muovitieto/julkaisukirjasto/muut_julkaisut/

Woodn Industries Srl. (2012) *Woodn® in art.* Official website. (Cited 1.10.2015) Available at: http://www.woodn.com/homeENG.html

WRAP – Waste and Resources Action Programme. (2015) *Waste as a resource*. (Cited 7.5.2015) Available at: http://www.wrap.org.uk/waste-as-a-resource

Appendix 1: Tensile Strength Test Results

Table A1-1 Tensile strength test results for 4 mm thick specimens. * = breakage within extensometer gauge

Sample	Young's Modulus (Mpa)	Tensile Stress at Yield (Zero Slope) (Mpa)	Tensile Strain at Break (%)	Thickness (mm)	Width (mm)
1.1	971,00	9,467	1,97	4,67	25,27
1.2	1290,00	10,94	*	4,11	24,7
1.3	1210,00	10,52	1,9	4,21	25,14
1.4	no valid data				
1.5	1360,00	10,81	1,72	4,15	25,14
1.6	1190,00	10,36	*	4,37	25,2
1.7	1290,00	9,942	1,54	4,21	25,25
1.8	1230,00	10,52	2,03	4,1	25,16
1.9	1310,00	10,48	1,76	4,21	25,22
1.10	1280,00	10,67	*	4,07	25,04
1.11	1320,00	10,45	1,78	4,19	25,12
1.12	1300,00	10,07	1,61	4,3	25,34
Mean	1250,09	10,38	1,79	4,24	25,14
Standard deviation	105,19	0,42	0,17	0,17	0,17

Table A1-2 Tensile strength test results for 2 mm thick specimens.

Sample	Young's Modulus (Mpa)	Tensile Stress at Yield (Zero Slope) (Mpa)	Tensile Strain at Break (%)	Thickness (mm)	Width (mm)
2.1	1730	no data	1,95	2,18	25,09
2.2	1930	16,22	1,49	1,96	25,2
2.3	1810	12,23	1,43	1,96	25,2
2.4	1890	15,63	1,57	2,01	25
2.5	2040	18,03	1,93	1,98	24,99
2.6	1830	16,04	1,66	2,06	24,99
2.7	1860	16,84	1,95	2,1	25,08
2.8	1860	16,22	1,71	2,07	25,22
2.9	1840	15,73	1,6	2,07	25,18
2.10	1650	12,73	1,34	2,17	25,08
Mean	1844	15,52	1,66	2,06	25,10
Standard deviation	105,28	1,87	0,22	0,08	0,09

Appendix 2: Water Absorption Test Results

Table A2-1 Water absorption test values in 22 °C water immersion.

		Before drying				After drying				After soaking			
Sample	Type	length 1	width 1	thickness 1	mass 1	length 2	width 2	thickness 2	mass 2	length 3	width 3	thickness 3	mass 3
1	2 mm	61,72	60,83	2,17	8,219	61,48	60,58	2,2	8,132	61,74	61,41	2,29	8,878
2	2 mm	60,48	61,81	2,11	7,997	60,47	61,43	2,15	7,912	60,54	62,57	2,3	8,608
3	2 mm	61,48	61,41	2,21	8,254	61,3	61,21	2,17	8,175	61,65	62,17	2,23	8,868
4	2 mm	61,49	60,45	2,19	8,252	61,83	59,99	2,2	8,17	62,05	60,54	2,32	8,847
5	2 mm	61,89	61,47	2,17	8,441	61,65	61,29	2,25	8,363	61,91	62,1	2,45	9,045
6	2 mm	60,12	61,62	2,1	8,133	60,07	61,7	2,15	8,055	60,21	62,08	2,29	8,716
7	2 mm	61,44	60	2,2	8,106	59,47	61,33	2,18	8,023	59,57	62,27	2,46	8,716
8	2 mm	61,26	62	2,17	8,327	61,19	61,95	2,11	8,247	61,43	62,56	2,25	8,947
9	2 mm	61,91	60,88	2,23	8,365	60,9	60,89	2,2	8,281	60,85	62,4	2,46	9,015
10	2 mm	60,29	61,07	2,25	7,928	60,99	60,22	2,11	7,844	60,4	61,57	2,31	8,572
11	4 mm	60,53	61,26	4,03	15,737	60,53	61,6	3,91	15,648	60,59	61,77	4,03	16,337
12	4 mm	61,27	60,9	3,85	15,873	61,24	61	3,8	15,783	61,35	61,23	4,01	16,519
13	4 mm	60,82	61,15	3,85	15,486	60,97	60,7	3,83	15,397	60,95	60,85	4,09	16,092
14	4 mm	60,17	61,22	3,81	15,492	60,23	61,29	3,86	15,402	60,28	61,04	3,97	16,094
15	4 mm	61,29	61	3,82	15,619	61,34	61,1	3,82	15,525	61,42	61,23	4,05	16,256
16	4 mm	62	60,58	3,88	15,807	62,08	61,01	3,8	15,707	62,16	61,15	3,98	16,446
17	4 mm	60,03	61,32	3,82	15,5	59,91	61,47	3,84	15,404	59,95	61,38	4,01	16,098
18	4 mm	60,25	61,38	3,81	15,468	60,23	61,48	3,82	15,371	60,32	61,51	4,04	16,068
19	4 mm	61,38	60,84	3,96	15,908	61,37	60,96	3,86	15,811	61,42	61,44	4,11	16,492
20	4 mm	61,1	60,94	3,91	15,589	61	60,65	3,84	15,491	61,27	60,9	4,1	16,162
21	2 mm soft	61,86	60,22	2,02	7,335	61,65	60,28	2,11	7,265	61,97	61,06	2,21	7,866
22	2 mm soft	60,93	60,84	2,12	6,904	60,6	60,55	2,03	6,832	60,78	61,85	2,17	7,508
23	2 mm soft	61,02	61,29	2,1	6,931	61,23	61,58	2,05	6,847	61,48	62,72	2,21	7,542
24	2 mm soft	61,04	61,66	2,07	6,987	60,83	61,76	2,02	6,917	61,18	62,93	2,3	7,634
25	2 mm soft	61,91	60,54	2,08	6,86	61,99	60,42	2,06	6,787	61,95	61,07	2,16	7,454
26	2 mm soft	61,98	60	2,02	6,793	61,44	59,55	2,04	6,722	61,51	60,67	2,26	7,369
27	2 mm soft	60,88	60,93	2,07	7,147	60,74	60,55	2,01	7,077	61,34	61,45	2,13	7,667
28	2 mm soft	60,69	60,7	2	7,167	60,52	60,7	2,05	7,098	60,75	61,62	2,09	7,676
29	2 mm soft	61,82	61,84	2,01	7,524	61,61	61,47	2,03	7,449	61,8	62,13	2,18	8,07
30	2 mm soft	61,82	61,67	1,98	7,49	61,87	61,41	1,98	7,411	61,99	62,03	2,1	8,018

Table A2-2 Water absorption test volume, mass and density changes in 22 °C water immersion.

		after drying			22 °C	after soaking		
sample	Type	ΔV1 (%)	Δm1 (%)	Δρ1 (%)		ΔV2 (%)	Δm2 (%)	Δρ2 (%)
1	2 mm	-0,573	-1,059	-1,622		5,628	9,174	3,030
2	2 mm	-1,253	-1,063	-2,287		8,331	8,797	-0,267
3	2 mm	2,416	-0,957	1,495		4,737	8,477	3,338
4	2 mm	-0,243	-0,994	-1,234		6,367	8,286	1,392
5	2 mm	-2,982	-0,924	-3,793		9,742	8,155	-2,381
6	2 mm	-2,429	-0,959	-3,307		6,905	8,206	0,734
7	2 mm	1,960	-1,024	0,955		12,866	8,638	-5,340
8	2 mm	2,954	-0,961	2,054		7,499	8,488	0,352
9	2 mm	2,939	-1,004	1,993		12,662	8,864	-4,920
10	2 mm	6,454	-1,060	5,766		9,788	9,281	-1,416
11	4 mm	2,439	-0,566	1,920		3,341	4,403	0,916
12	4 mm	1,185	-0,567	0,625		5,762	4,663	-1,368
13	4 mm	1,008	-0,575	0,438		6,557	4,514	-2,339
14	4 mm	-1,529	-0,581	-2,078		2,454	4,493	1,929
15	4 mm	-0,246	-0,602	-0,845		6,002	4,709	-1,576
16	4 mm	1,239	-0,633	0,614		4,864	4,705	-0,388
17	4 mm	-0,568	-0,619	-1,181		4,163	4,505	0,155
18	4 mm	-0,392	-0,627	-1,016		5,633	4,535	-1,354
19	4 mm	2,349	-0,610	1,781		6,892	4,307	-2,882
20	4 mm	2,418	-0,629	1,833		7,137	4,332	-3,115
21	soft	-4,205	-0,954	-4,951		6,231	8,273	1,526
22	soft	5,218	-1,043	4,405		8,689	9,895	0,346
23	soft	1,582	-1,212	0,376		9,296	10,150	-0,089
24	soft	2,593	-1,002	1,634		14,300	10,366	-5,416
25	soft	1,030	-1,064	-0,034		5,584	9,828	3,695
26	soft	0,641	-1,045	-0,407		11,502	9,625	-2,984
27	soft	3,726	-0,979	2,853		7,925	8,337	-0,249
28	soft	-2,213	-0,963	-3,107		3,744	8,143	4,094
29	soft	-0,050	-0,997	-1,046		8,153	8,337	-0,496
30	soft	0,341	-1,055	-0,716		6,837	8,191	0,793

Table A2-3 Water absorption test average values for volume, mass and density changes in 22 °C water immersion.

		after drying			22 °C	after soaking		
Samples	Type	Average ΔV1 (%)	Average Δm1 (%)	Average Δρ1 (%)		Average ΔV2 (%)	Average Δm2 (%)	Average Δρ2 (%)
1-10	2 mm	0,924	-1,000	0,002		8,453	8,637	-0,548
11-20	4 mm	0,790	-0,601	0,209		5,280	4,517	-0,759
21-30	soft	0,866	-1,031	-0,099		8,226	7,746	-0,869

Table A2-4 Water absorption test values in 70 °C water immersion.

		Before drying				After drying				After soaking			
Sample	Type	length 1 (	width 1	thickness 1	mass 1	length 2 (	width 2	thickness 2	mass 2	length 3 (	width 3	thickness 3	mass 3
31	2 mm	60,77	60,85	2,2	8,297	60,8	61,03	2,17	8,203	N/A	N/A	N/A	16,966
32	2 mm	61,77	60	2,12	7,952	61,67	59,97	2,16	7,858	N/A	N/A	N/A	14,923
33	2 mm	61,02	61,81	2,18	8,438	60,85	61,65	2,2	8,343	N/A	N/A	N/A	16,386
34	2 mm	61,9	61,49	2,18	8,516	61,46	61,53	2,22	8,423	N/A	N/A	N/A	15,479
35	2 mm	61,43	61,52	2,17	8,547	61	61,26	2,18	8,446	N/A	N/A	N/A	15,255
36	2 mm	60,37	60,91	2,15	8,009	61,27	60,23	2,14	7,92	N/A	N/A	N/A	15,909
37	2 mm	61,81	62	2,14	8,519	61,81	62	2,28	8,42	N/A	N/A	N/A	15,401
38	2 mm	61,65	61,52	2,25	8,398	61,35	61,14	2,27	8,302	N/A	N/A	N/A	15,412
39	2 mm	61,19	60,65	2,16	8,091	61,39	60,43	2,15	7,99	N/A	N/A	N/A	15,108
40	2 mm	60,69	62	2,27	8,361	61,95	60,42	2,15	8,262	N/A	N/A	N/A	15,467
41	4 mm	61,32	60,73	3,83	15,485	61,27	60,42	3,81	15,384	N/A	N/A	N/A	28,75
42	4 mm	61,31	61,17	3,8	15,543	61,33	61,2	3,84	15,444	N/A	N/A	N/A	29,819
43	4 mm	61,51	61,06	4,14	15,666	61,36	60,94	3,85	15,568	N/A	N/A	N/A	28,813
44	4 mm	61,68	60,76	3,87	15,54	61,5	60,65	3,87	15,442	N/A	N/A	N/A	30,279
45	4 mm	61,33	60,74	3,96	15,695	61,43	60,94	3,81	15,597	N/A	N/A	N/A	30,241
46	4 mm	61,3	61,11	3,9	15,897	61,3	61,13	3,83	15,801	N/A	N/A	N/A	30,534
47	4 mm	61	61,01	3,89	15,748	61,15	61,07	3,83	15,647	N/A	N/A	N/A	31,615
48	4 mm	60,71	61,15	3,8	15,666	61,08	60,65	3,84	15,565	N/A	N/A	N/A	30,642
49	4 mm	60,41	60,76	3,85	15,449	60,43	60,69	3,84	15,348	N/A	N/A	N/A	30,305
50	4 mm	61,05	60,64	3,89	15,704	61,01	60,73	3,82	15,594	N/A	N/A	N/A	29,851
51	soft	61,66	60,41	2,09	6,712	61,76	60,42	1,99	6,631	N/A	N/A	N/A	11,843
52	soft	61,94	61,47	2,08	7,062	61,93	61,43	2,02	6,976	N/A	N/A	N/A	12,624
53	soft	60,05	61,95	2,02	6,768	60,02	62,14	1,98	6,69	N/A	N/A	N/A	11,932
54	soft	60,06	61,25	1,99	6,552	59,93	60,99	1,94	6,474	N/A	N/A	N/A	11,505
55	soft	61,12	60,6	2,04	6,713	61,26	60,23	1,97	6,632	N/A	N/A	N/A	11,691
56	soft	60,19	61,2	2,05	6,936	60,06	60,91	2,09	6,865	N/A	N/A	N/A	12,22
57	soft	60,9	61,91	2,06	7,247	60,84	61,76	2,08	7,17	N/A	N/A	N/A	13,006
58	soft	62,02	61,29	2,04	7,378	61,76	61,3	1,98	7,293	N/A	N/A	N/A	13,232
59	soft	61,7	61,18	2,05	7,126	61,38	60,67	1,97	7,047	N/A	N/A	N/A	12,882
60	soft	61,15	61,86	2,06	7,277	61,08	61,73	2,03	7,192	N/A	N/A	N/A	13,022

Table A2-5 Water absorption test volume, mass and density changes in 70 °C water immersion.

		after drying			70 °C	after soaking		
sample	Type	ΔV1 (%)	Δm1 (%)	Δρ1 (%)		ΔV2 (%)	Δm2 (%)	Δρ2 (%)
31	2 mm	1,023	-1,133	-0,001		*	106,827	*
32	2 mm	-1,671	-1,182	-0,028		*	89,908	*
33	2 mm	-0,376	-1,126	-0,015		*	96,404	*
34	2 mm	-1,177	-1,092	-0,022		*	83,771	*
35	2 mm	0,664	-1,182	-0,005		*	80,618	*
36	2 mm	0,109	-1,111	-0,010		*	100,871	*
37	2 mm	-6,542	-1,162	-0,072		*	82,910	*
38	2 mm	0,222	-1,143	-0,009		*	85,642	*
39	2 mm	0,500	-1,248	-0,008		*	89,086	*
40	2 mm	5,784	-1,184	0,049		*	87,206	*
41	4 mm	1,111	-0,652	0,005		*	86,882	*
42	4 mm	-1,135	-0,637	-0,018		*	93,078	*
43	4 mm	7,414	-0,626	0,073		*	85,078	*
44	4 mm	0,472	-0,631	-0,002		*	96,082	*
45	4 mm	3,314	-0,624	0,028		*	93,890	*
46	4 mm	1,763	-0,604	0,012		*	93,241	*
47	4 mm	1,203	-0,641	0,006		*	102,052	*
48	4 mm	-0,837	-0,645	-0,015		*	96,865	*
49	4 mm	0,342	-0,654	-0,003		*	97,452	*
50	4 mm	1,718	-0,700	0,010		*	91,426	*
51	soft	4,614	-1,207	0,036		*	78,601	*
52	soft	2,963	-1,218	0,018		*	80,963	*
53	soft	1,729	-1,152	0,006		*	78,356	*
54	soft	3,137	-1,190	0,020		*	77,711	*
55	soft	3,801	-1,207	0,027		*	76,282	*
56	soft	-1,249	-1,024	-0,022		*	78,004	*
57	soft	-0,627	-1,063	-0,017		*	81,395	*
58	soft	3,332	-1,152	0,023		*	81,434	*
59	soft	5,198	-1,109	0,043		*	82,801	*
60	soft	1,776	-1,168	0,006		*	81,062	*

Table A2-6 Water absorption test average values for volume, mass and density changes in 70 °C water immersion.

		after drying			70 °C	after soaking		
Samples	Type	Average ΔV1 (%)	Average Δm1 (%)	Average Δρ1 (%)		Average ΔV2 (%)	Average Δm2 (%)	Average Δρ2 (%)
31-40	2 mm	-0,1463748	-1,10828	-0,01163		*	88,32995	*
41-50	4 mm	1,5364083	-0,69685	0,012776		*	92,77649	*
51-60	soft	2,4674357	-1,14247	0,011506		*	87,51435	*

Appendix 3:

Workshop Pre-assignment

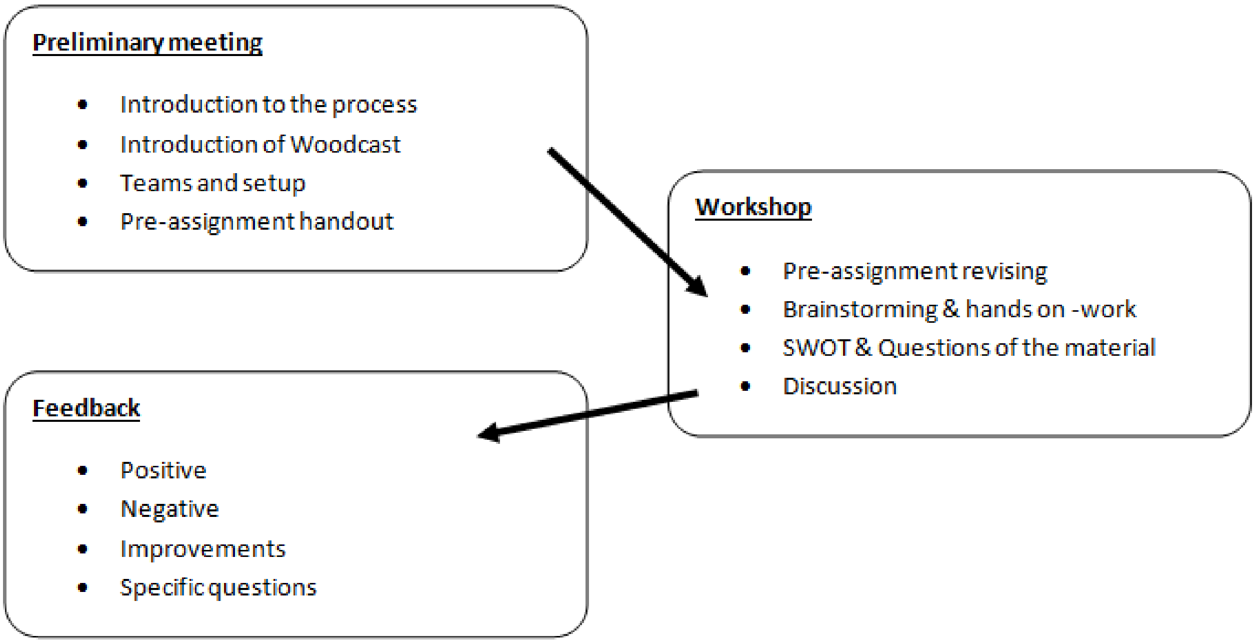
This pre-assignment is meant to be done based on the information you get from the demonstration in the lecture and from Woodcast® –website. Own visions and ideas are more than welcome; use your imagination and intuition!

To Do –list for the workshop session:

- Visit Woodcast®'s webpage at: http://www.woodcast.fi/en
- Write down 5-10 novel application possibilities for Woodcast®.
- Choose one of your application suggestions and make a shortSWOT –analysis of it.

Submit the pre-assignment to victoria.eklund@aalto.fi at the latest on Wednesday 25th of February. All questions can also be sent to the above mentioned address.

Ps. here's the workshop structure for you.



Appendix 4:

Workshop Instructions

This is what we will do today:

1. Pre-assignment look through
2. Brainstorming
3. Hands on –work in teams
4. Introducing the results of the teamwork and questions of the material
5. Discussion with the whole group

I would be very pleased to get your notes you make during the workshop. Write them on this paper or on something you can easily share. Of course you can get your notes back, if you want.

Appendix 5:

Workshop Participant Feedback

What is your general impression of the material?

Do you think that there could be commercial applications for the material? (Examples, if you have some!)

Is a workshop a good way to evoke thoughts and questions? How?

Does this kind of workshop bring perspective to composite materials? Did it give something new to you?

Were the tasks and hand-outs easy to understand?

Improvement ideas:

Additional feedback for workshop organizer:

Thank you for participating!